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Vol. XII, No. 5 *PSYCHOLOGICAL REVIEW PUBLICATIONS* OCTOBER, 1929

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Journal of Experimental Psychology

EDITED BY

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RAYMOND DODGE, YALE UNIVERSITY (*Monographs*)
S. W. FERNBERGER, UNIVERSITY OF PENNSYLVANIA (*Bulletin*)
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PUBLISHED BI-MONTHLY
FOR THE AMERICAN PSYCHOLOGICAL ASSOCIATION
BY THE PSYCHOLOGICAL REVIEW COMPANY
PRINCE AND LEMON STS., LANCASTER, PA.
AND PRINCETON, N. J.

Entered as second-class matter, July 1, 1920, at the post-office at Lancaster, Pa.

Psychological Review Publications

of the American Psychological Association

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PSYCHOLOGICAL REVIEW COMPANY
PRINCETON, N. J. OFFICE

Journal of
Experimental Psychology

VOL. XII, No. 5 OCTOBER, 1929

INTENSITY OF LIGHT AND SPEED OF VISION

BY C. E. FERREE AND GERTRUDE RAND

Research Laboratory of Physiological Optics, Wilmer Ophthalmological Institute, Johns Hopkins Medical School

I. EFFECT OF SIZE OF OBJECT AND DIFFERENCE OF COEFFICIENT OF REFLECTION AS BETWEEN OBJECT AND BACKGROUND

It is obvious that the effect of intensity of light upon speed of vision may be studied in relation to a number of pertinent factors. We have selected for a series of studies a group of these factors which sustains an important relation to conditions found in the industries and also in other representative uses of the eye.[1]

The industrial test is the ultimate test of lighting in relation to industry. It is often of great advantage, however, to precede and to supplement the industrial test by appropriately selected laboratory studies, which, by disclosing the factors involved and by showing the comparative importance of their effects under various conditions sampled from industrial situations, provide a more intelligent basis for planning the more unmanageable and unwieldy industrial study and for interpreting the results there obtained. In connection with the work of the National Research Council's Committee a program combining both of these types of study was planned for investigating intensity of light in relation to industrial needs. As one item in this program a series of studies has been undertaken to show the effect of intensity of light on the speed of the eye's reactions, supplemented by a study of the comparative importance of speed of vision to speed of work, which is designed to furnish a more complete explanation of the effect of intensity of light upon the speed with which the eye can discriminate detail.

In the present paper results will be presented for only a part of the work on the effect of intensity of light upon speed. In this connection it is but reasonable to suppose that the effect will also depend a great deal upon numerous other

[1] The studies were made under the auspices of the National Research Council's Committee on Industrial Lighting.

factors influencing the eye's power to discriminate detail. Among these factors may be mentioned size of visual angle, ratio of coefficient of reflection of work to its background, and the following illumination factors, evenness of distribution, diffuseness, angle of incidence upon the work and glare in the field of view and on the working surface.

A great deal of work has been done in our previous studies to show the effect of the latter class of factors on ocular fatigue, ocular discomfort, and the power to sustain clear vision. Also an attempt has been made to analyze and to explain the effect of these factors on the more important ocular functions. As yet, however, no extensive determination has been made of their effect on speed of vision and its correlative function, power to sustain speed of vision. Nevertheless it may not be out of place to emphasize at this point that a fair trial can not be made of the benefit of increase of intensity of light on the speed of the eye's performance or on the speed of work unless due care is taken in the control of the illumination factors. The eye can not be expected *e.g.* to respond as it should to increase of intensity of light if the means employed to secure the increase of intensity introduces a harmful glare into the field of view or increases unduly the amount of glare on the working surface. In short, the attempt to raise the standard of intensity in lighting practice again revives acutely the problems which cluster about the effective adaptation of light to illumination.

It is the chief purpose of the present investigation to study the effect of change of intensity of light over a wide range on the speed of vision in the presence of two variables: size of work and difference in coefficient of reflection between the work and its background. Sizes have been chosen subtending visual angles of 1, 2, 3, 4.2 and 5.2 minutes of arc, and backgrounds having coefficients of reflection of 78, 29, 21 and 16 percent. The visual angles selected have been considered representative of sizes of work for which changes of intensity of light have an important ocular effect; the coefficients of reflection respectively approximate those of a white surface of good reflecting power, polished steel and brass, unpolished steel and brass, and iron. The range of illuminations covered extends in most cases from the lowest value practicable for a speed determination to 100 ft.c. The determinations were made with the special purpose of obtaining information on the following points: (1) the comparative importance of changes in size of work, differences in coefficient of reflection between object and background, and intensity of illumination as factors influencing the speed of the eye's response; (2) the influence of size of work and difference in coefficient of reflection between the work and its background on the range of speeds given by the intensities of illumination selected; and (3) the influence of both of these factors on the shape, the sharpness of inflection, and the location of the knee of the curve representing the changes in the speed of the eye's response.

Among other points calling for further research may be mentioned (1) the effect of certain typical or representative differences in color between object and background, (2) a comparison of the effect of a dark object on a light background and a light object on a dark background, (3) a determination of the effect of the position of the difference between object and background in the scale of coefficients of reflection and (4) the influence of the form and complexity of object and the degree of complication of the task set for the eye. We have also undertaken (a) to determine the ratio of speed of vision to the speed of the visual-motor reaction over a wide range of intensities of

illumination and the influence of change of intensity on this ratio, (b) to compare the time required for the eye just to discriminate its object with the time which it actually takes in making the discrimination in a series of visual acts when working at maximal speed, and (c) to make a more complete analysis and evaluation of the factors which affect acuity and speed of vision, more particularly in relation to their influence on the effect of intensity of light.

In lighting practice there has always been a tendency to reduce to some simple type of formulation the relation of intensity of light to human needs. That a simple formulation is not compatible with the economic needs of the eye does not require a very elaborate investigation to demonstrate. The effect of intensity of light on the speed of its reaction is, for example, complicated by all of the factors which affect acuity and the rate of rise of visual sensation. In this list of factors, as already stated, size of object and difference in coefficient of reflection between the object and its background occupy a very important place, the former more important within practical limits, it would seem, than intensity itself. It is obvious therefore that these factors at least must be taken into account in any attempt at a formulation of this kind.

In the problem of adapting any given amount or intensity of light to the purposes of illumination we have come to recognize a set of factors which have been variously called illumination factors, distribution factors, etc. In the choice of the amount of light to be used for various types of work, we are similarly confronted with another very important set of factors which may be tentatively called the intensity factors. In connection with the question of formulation in the presence of these factors, perhaps the best that can be hoped for at present is a determination of the types of work for which a measurable benefit of increase of intensity may be expected and a rough specification of the range of intensities which offers the greatest possibilities of benefit for various types of work. In this connection it should be mentioned too that speed of vision is only one of the ocular benefits of increase of intensity of light and that speed of work is not the only measure of merit in the relation of illumination to the industries.

The Experiments

It was our wish to conduct the tests for the effect of increase of intensity of light on speed of vision with a good control of all the illumination factors and one that would be uniform from intensity to intensity. Also, when needed, we wished to be able to vary the general illumination of the room in finely graded steps. These conditions of control for the wide range of intensities required could best be obtained from daylight illumination. The tests were conducted, therefore, in a daylighted optics room especially fitted up for the purpose.

This room was 16 ft long, 13 ft wide and 12 ft high. The walls were painted a mat white and the floor a light gray. The room was provided with two windows on one side, 3 ft × 6 ft, and a skylight 12 ft × 9 ft. Beneath the skylight was a light-well 8 ft deep at one end and 5 ft at the other. The walls of this light-well were

painted mat white. Beneath the light-well were swung two diffusion sashes of ground glass, each 12 ft × 4.5 ft. All of the light entering the room from the light-well passed through these sashes. To provide for the ventilation of the room the sashes were dropped 11 in below the opening of the light-well.

In order to provide for the control and variation of the amount of daylight entering the light-well, two sets of curtains were installed directly beneath the skylight, one set consisting of four overlapping light-proof curtains to provide for the gross changes, the other of three thin white curtains to give the finer changes often needed in maintaining constancy of illumination. Beneath the diffusion sashes were also installed three sets of curtains, one a broad light-proof curtain covering the entire ceiling of the room, the edges of which were enclosed to a depth of several inches in a light-tight boxing; and two sets of thin white curtains, one running lengthwise of the room and the other crosswise. These two systems of curtains could be used singly or in combination as might be needed. By these means very minute changes of intensity could be made and the room was illuminated at all intensities by a soft, evenly distributed, well-diffused light which gave no glare either on the working surface or anywhere in the field of view. The windows were also provided with light-proof curtains for the gross, and thin white curtains for the fine changes in illumination. Each of the light-proof curtains, overhead and window, was painted mat white on the inside.

The experiments were conducted at intensities of illumination ranging from 1.25 to 100 ft.c. at the test-surface. At each intensity the vertical and horizontal components of illumination were made equal. This was done in order that the size of pupil should not be influenced by an intensity of light higher than that coming from the test-surface. In making the equalization, two duplicate test-plates for the Macbeth Illuminometer were mounted at right angles to each other on a tripod stand.

This stand was so placed that the vertical plate was inserted in the position of the test-surface and gave the measure of the horizontal component of illumination, while the second plate mounted at the level of its lower edge furnished the measure of the vertical component. Supplementary tests showed that if this control of the two components of illumination was not exercised, a difference in result was obtained. It was deemed best, therefore, to control both components, the purpose being to conduct our foundation series of experiments under conditions as nearly as possible free from the influence of all variables but the one under investigation. The additional light used to increase the horizontal component could in most cases be obtained from the two curtained windows. In the cases in which sufficient light could not be obtained from the windows, additional light was supplied from a Macbeth artificial daylight unit. Frequent measurements were made of both the horizontal and the vertical components of illumination during each series of exposures contributing to one determination of speed, and great care was taken that the determinations were always made at the intensity specified.

The tests were made with the rotary tachistoscope used in former studies.[2] In order to provide for the wide range of exposure-times needed, a series of special gears was made designed to give low, medium and high speeds of rotation of the disc. The broken circle (i.e. the international test-object) mounted at the center of a rotatable, graduated dial was used as test-object. In making the observation all that was required of the observer was to indicate the direction in which the opening pointed. The judgment was thus reduced to very simple terms and an objective check was had on its correctness.

Eight positions of the opening of the circle, presented in haphazard order, were used (up, down, right, left and the four 45 deg. positions). A correct judgment was required in five out of the eight positions in the determination of the exposure-time needed for the discrimination of the test-object. The breadth of the opening was measured in each case on a micrometer comparator and the visual angle computed. The distance from the eye was 2.5 meters. On the front surface of the exposure discs in line with the observer's eye and the test-object was placed a fixation cross in order that the exposure might begin with the eye in approximate adjustment for the test-object. Constancy of position of the eye was secured by biting a mouthboard in which the impression of the teeth had been previously made and hardened in wax. The pre-exposure and surrounding field were made in each case of the same brightness as the test-surface. The eye was allowed to adapt to each intensity of light through a 30-min practice series provided with proper rest periods. Great care was taken to keep the eye in an unchanging state of adaptation and to prevent fatigue. The fatigued eye becomes slow and very erratic. Not only do adequate rest periods have to be provided during the course of the experiment, but extreme care has to be taken not to overtax the eyes during the days, weeks or months, as the case may be, in which the experiments are being conducted. Unless a rigorous control is had of the factors of adaptation and fatigue, accuracy and precision of result can not be hoped for in any of the more delicate tests of acuity.

Because of the extended scope of the study and the need for comparison of the results on every point, it has been possible thus far to conduct the tests on only one observer, R. It is our intention later in the study to verify on other trained observers some of the more important results obtained, particularly the location of the knee of the curve under the various conditions. Comparisons have been made of Obs. R's speed with that of other observers, trained and untrained, under the same test conditions. These comparisons have shown that this observer ranks approximately average in a group of trained observers selected with special reference to good refraction, muscle balance, etc.; and is in the upper quartile when compared with a group of untrained, unselected observers.

---

[2] See the following articles. The effect of variations in intensity of illumination on functions of importance to the working eye, *Trans. I.E.S.*, 1920, *15*, 769–792; The effect of variation of visual angle, intensity and composition of light on important ocular functions, *ibid.*, 1922, *17*, 69–86; Further studies on the effect of composition of light on important ocular functions, *ibid*, 1924, *19*, 424–447.

Only the right eye was used. The left eye was open but screened from the test-object by a white card attached to the mouthboard. Preliminary studies showed that this observer's speed was very nearly the same with the right eye as with both eyes. The monocular condition was chosen, therefore, in order that a comparison might be made of the speed of vision with the natural and with an artificial pupil. This comparison could not have been made with binocular vision.

Results

The determinations of speed were made at illuminations ranging from 1.25 to 100 ft.c. for five sizes of opening of broken circle or detail to be discriminated (1, 2, 3, 4.2 and 5.2 min of arc) on backgrounds having different coefficients of reflection (78, 29, 21 and 16 percent).

In presenting the data it has been deemed advisable first to plot for gross comparison all the results obtained under the various conditions on the same value of coördinates, and in later charts to replot them to bring out special points for comparison. The massed data plotted on the same value of coördinates are shown in Fig. 1. Illumination in ft.c. is plotted on the horizontal, and speed taken as the reciprocal of the time required to make the discrimination on the vertical coördinate. For the convenience of the reader, on the extreme right of the chart is noted also the time in seconds corresponding to various points on the scale of reciprocals. Since time values do not space equally on this scale, intermediate points can not, of course, be obtained from the chart by direct interpolation.

Among the points of general interest to be noted in these curves are (1) the high speeds obtained with large visual angles and large differences in coefficient of reflection between object and background; (2) the greater total percentage of increase of speed with increase of intensity for the smaller visual angles and the smaller differences in coefficient of reflection between object and background; (3) the more rapid initial rise and the sharper inflection of the curve for the larger visual angles and the larger differences in coefficient of reflection between object and background, due to the greater concentration of the effect of increase of intensity into the lower part of the scale; and (4) the rough equivalence of certain combinations

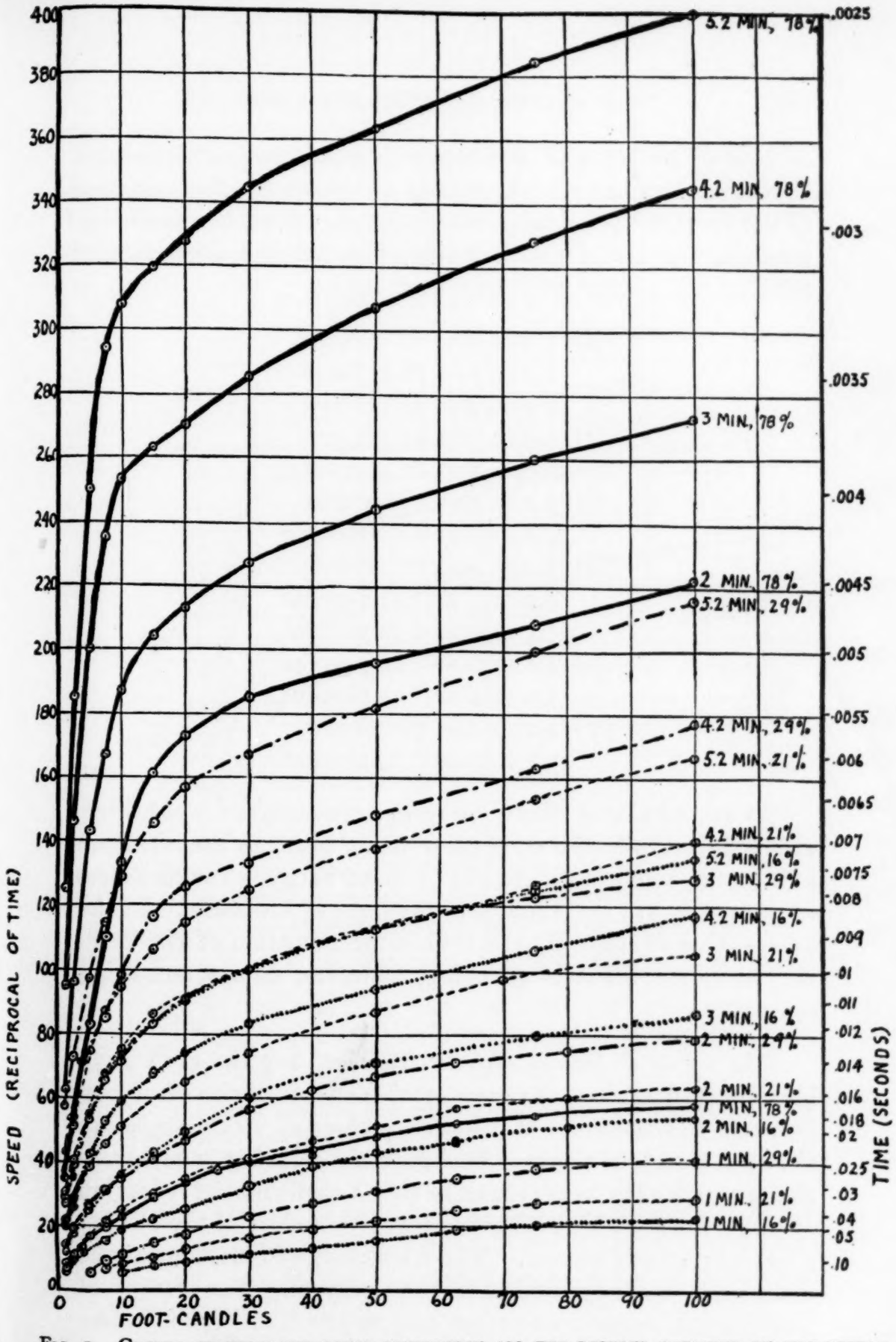

FIG. 1. CURVES SHOWING FOR GROSS COMPARISON ALL THE RESULTS OBTAINED ON THE EFFECT OF INCREASE OF INTENSITY OF LIGHT ON SPEED OF VISION.

The studies were made with special reference to the influence of size of object and difference in coefficient of reflection between object and background. Sizes of object 1, 2, 3, 4.2 and 5.2 min. visual angle. Coefficient of reflection of object 3–4 percent; of background 78, 29, 21 and 16 percent. Speed (reciprocal of time) plotted against foot-candles.

of size of object and difference in coefficient of reflection between object and background, as shown by the grouping of the curves. With reference to this last point the following groupings of combination of size of object and coefficient of reflection of background may be noted:

(*a*) 2 min and 16 percent
1 min and 78 percent
2 min and 21 percent
(*b*) 2 min and 29 percent
3 min and 16 percent
(*c*) 3 min and 21 percent
4.2 min and 16 percent
(*d*) 3 min and 29 percent
4.2 min and 21 percent
5.2 min and 16 percent
(*e*) 4.2 min and 29 percent
5.2 min and 21 percent
(*f*) 2 min and 78 percent
5.2 min and 29 percent

As stated above, these groupings are rough; *i.e.* considerable differences in speed are often found between the members of a group, also the differences in speed between the members of the group are not equal for all values of intensity. In the perspective afforded by the massed presentation of the data, the tendency towards grouping, however, comes out quite clearly.

The Effect of Size of Object. In Figs. 2–5 the data have been plotted to show the comparative effects of size of object. In these charts curves for the five values of visual angle are shown for each of the four backgrounds. In Fig. 2 are given the results for the background having a coefficient of reflection of 78 percent. This background was the white of the Hering series of pigment papers. The coefficient of reflection of the test-object was approximately 3 percent. The range of illumination covered was from 1.25 to 100 ft.c. Speed taken as the reciprocal of the time required to make the discrimina-

tion is plotted on the vertical coördinate and (as in Fig. 1) the time corresponding to various points on the reciprocal scale is noted at the right of the chart. On the horizontal coördinate are plotted the intensity of illumination in ft.c.,

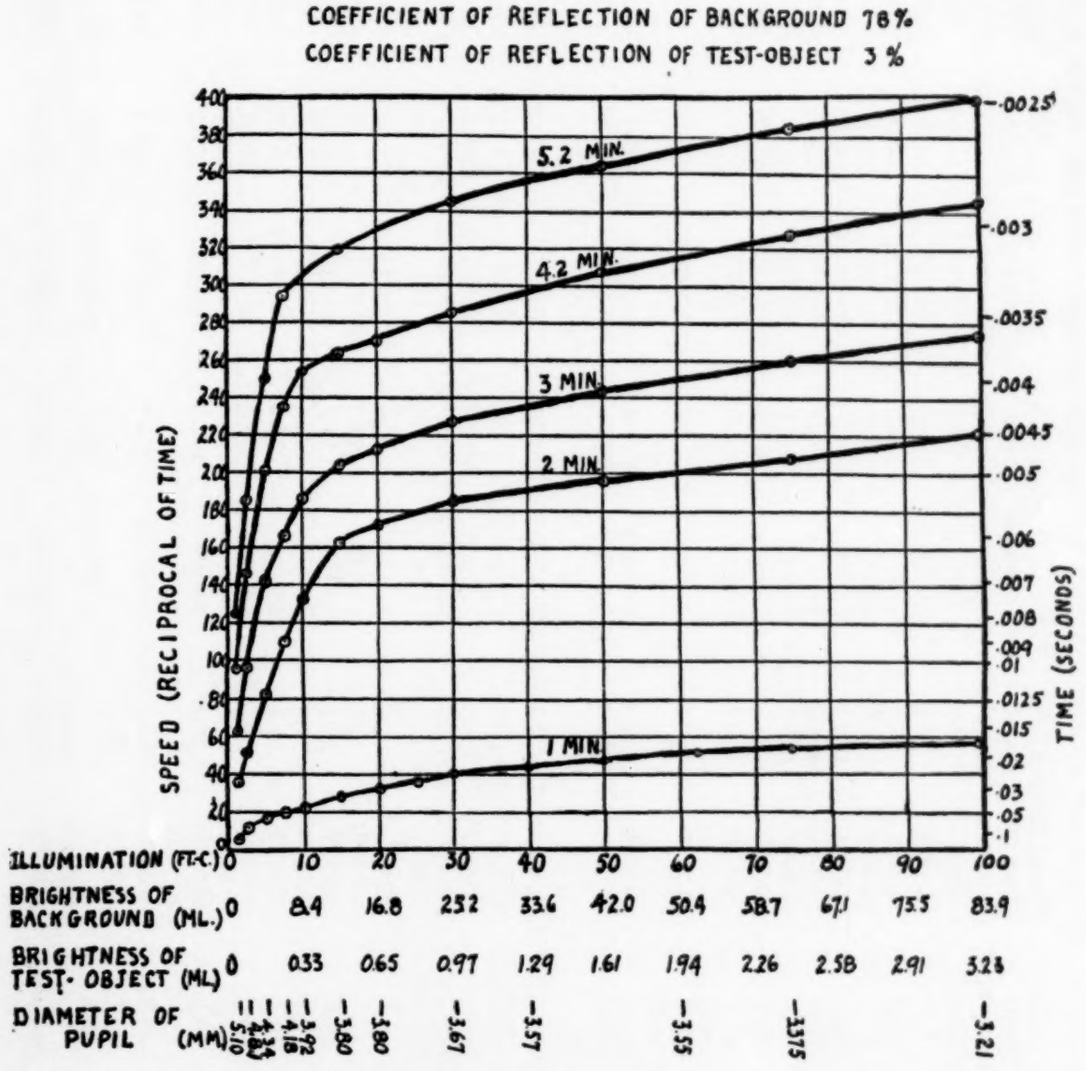
COEFFICIENT OF REFLECTION OF BACKGROUND 78%
COEFFICIENT OF REFLECTION OF TEST-OBJECT 3%
SPEED (RECIPROCAL OF TIME)
TIME (SECONDS)
5.2 MIN.
4.2 MIN.
3 MIN.
2 MIN.
1 MIN.
ILLUMINATION (FT.-C.) 0 10 20 30 40 50 60 70 80 90 100
BRIGHTNESS OF BACKGROUND (ML.) 0 8.4 16.8 25.2 33.6 42.0 50.4 58.7 67.1 75.5 83.9
BRIGHTNESS OF TEST-OBJECT (ML.) 0 .033 .065 .097 1.29 1.61 1.94 2.26 2.58 2.91 3.28
DIAMETER OF PUPIL (MM) -3.80 -3.67 -3.57 -3.55 -3.375 -3.21

FIG. 2. CURVES SHOWING THE COMPARATIVE EFFECTS OF THE FIVE SIZES OF OBJECT FOR THE BACKGROUND HAVING A COEFFICIENT OF REFLECTION OF 78 PERCENT; COEFFICIENT OF REFLECTION OF OBJECT 3 PERCENT.

and the brightness of both background and test-object in ml. Also on this coördinate is indicated the diameter of the pupil in mm at each of the intensities used in the experimental determinations.

DATA FOR CURVES IN FIG. 2. (COEFFICIENT OF REFLECTION OF BACKGROUND 78 PERCENT; OF TEST-OBJECT 3 PERCENT)

Illumination (Ft.C.)	Visual Angle 1 Min		Visual Angle 2 Min		Visual Angle 3 Min		Visual Angle 4.2 Min		Visual Angle 5.2 Min	
	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)
1.25	0.1500	6.7	0.0283	35.3	0.0160	62.5	0.0105	95.2	0.0080	125.0
2.50	0.0886	11.3	0.0195	51.3	0.0104	96.2	0.00685	146.0	0.0054	185.2
5.00	0.0608	16.5	0.0121	82.6	0.0070	142.9	0.0050	200.0	0.0040	250.0
7.50	0.0508	19.7	0.0091	109.9	0.0060	166.7	0.00425	235.3	0.0034	294.1
10.00	0.0442	22.6	0.0075	133.3	0.00535	186.9	0.00395	253.2	0.00325	307.7
15.00	0.0350	28.6	0.0062	161.3	0.0049	204.1	0.00380	263.2	0.00313	319.5
20.00	0.0300	33.3	0.0058	172.4	0.0047	212.8	0.00370	270.3	0.00305	327.9
30.00	0.0249	40.2	0.0054	185.2	0.0044	227.3	0.00350	285.7	0.00290	344.8
40.00	0.0226	44.3								
50.00	0.0210	47.6	0.0051	196.1	0.0041	243.9	0.00325	307.7	0.00275	363.6
62.50	0.0193	51.8								
75.00	0.0184	54.4	0.0048	208.3	0.00385	259.7	0.00305	327.9	0.00260	384.6
100.00	0.01725	58.0	0.0045	222.2	0.00365	274.0	0.00290	344.8	0.00250	400.0

DATA FOR CURVES IN FIG. 3. (COEFFICIENT OF REFLECTION OF BACKGROUND 29 PERCENT; OF TEST-OBJECT 4 PERCENT)

Illumination (Ft.C.)	Visual Angle 1 Min		Visual Angle 2 Min		Visual Angle 3 Min		Visual Angle 4.2 Min		Visual Angle 5.2 Min	
	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)
1.25			0.084	11.9	0.0372	26.9	0.0233	42.9	0.0173	57.8
2.50			0.0518	19.3	0.0248	40.3	0.0185	54.1	0.01375	72.7
5.00	0.172	5.8	0.0377	26.5	0.0187	53.5	0.0139	71.9	0.01025	97.6
7.50	0.112	8.9	0.0318	31.5	0.0153	65.4	0.01175	85.1	0.00875	114.3
10.00	0.0896	11.2	0.0285	35.1	0.0140	71.4	0.010125	98.8	0.00775	129.0
15.00	0.0690	14.5	0.0246	40.7	0.0120	83.3	0.00860	116.3	0.006875	145.5
20.00	0.0576	17.4	0.0216	46.3	0.0110	90.9	0.00795	125.8	0.006375	156.9
30.00	0.0436	22.9	0.0178	56.2	0.0100	100.0	0.00750	133.3	0.0060	166.7
40.00	0.0370	27.0	0.0160	62.5						
50.00	0.0325	30.8	0.0150	66.7	0.008875	112.7	0.00675	148.2	0.00550	181.8
62.50	0.0285	35.1	0.0140	71.4						
75.00	0.02625	38.1			0.008125	123.1	0.006125	163.3	0.0050	200.0
80.00			0.01335	74.9						
100.00	0.0247	40.5	0.0127	78.7	0.00775	129.0	0.005625	177.8	0.004625	216.2

Size of pupil should, as we believe, be specified in the presentation of data of this kind. It exerts an important influence on clearness of seeing, and secondly, it is influenced by other factors than intensity of light as ordinarily specified, namely, the area of the illuminated surface, high brilliancies in the field of view, and other com-

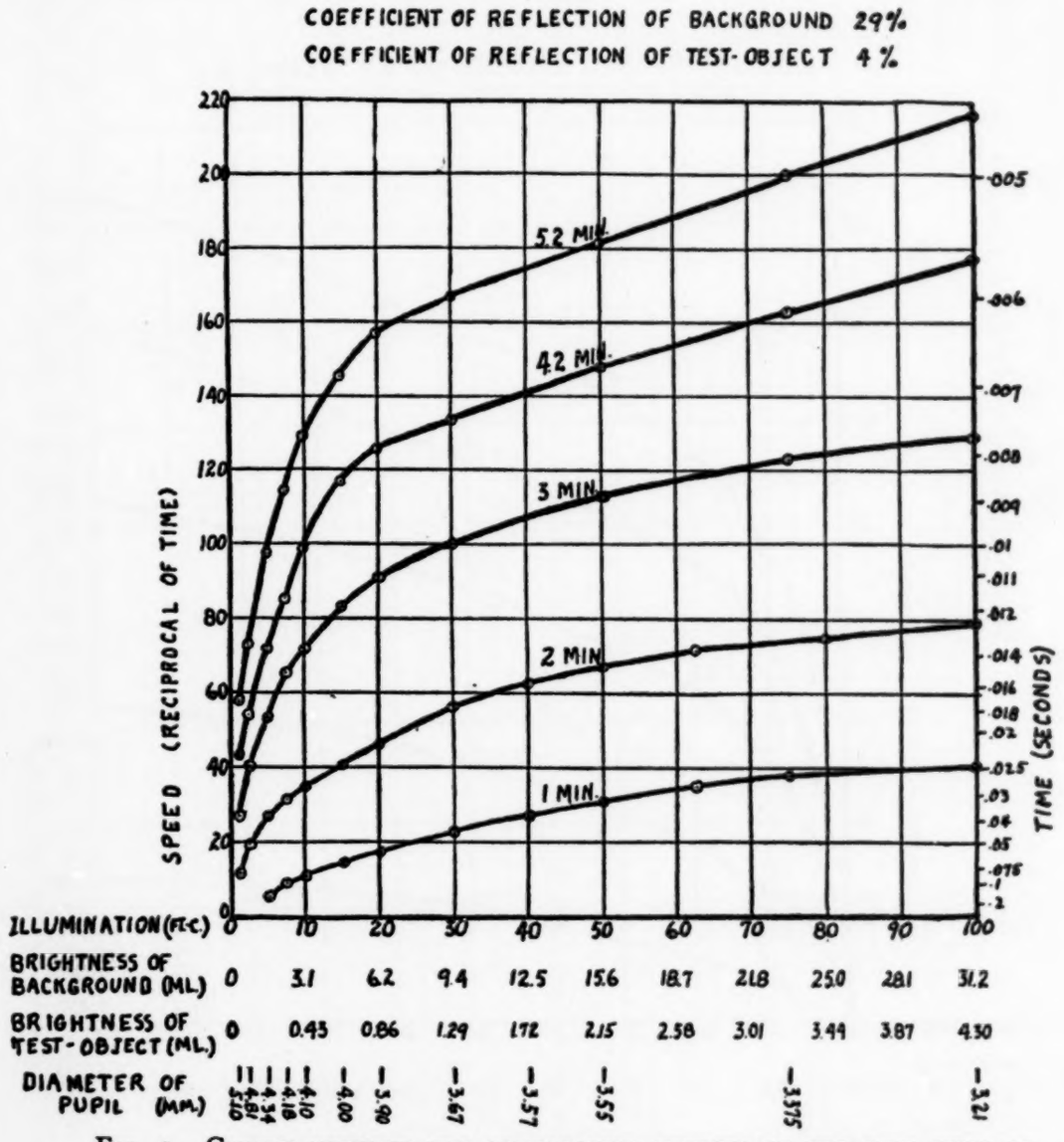

FIG. 3. CURVES SHOWING THE COMPARATIVE EFFECTS OF THE FIVE SIZES OF OBJECT FOR THE BACKGROUND HAVING A COEFFICIENT OF REFLECTION OF 29 PERCENT; COEFFICIENT OF REFLECTION OF OBJECT 4 PERCENT.

ponents of light besides the one coming from the surface directly viewed. In short, change in size of pupil is a composite reaction to the whole field of view and not alone to the object looked at. In the present series of experiments, for example, different results were obtained both for size of pupil and for speed of vision when the horizontal and vertical components of illumination were equalized and when they were not.

The effect of size of work on the speed of discrimination, on the location of the knee of the curve and on the shape of the curve is obvious from this chart. (1) Large increases of speed are produced at each intensity of illumination by

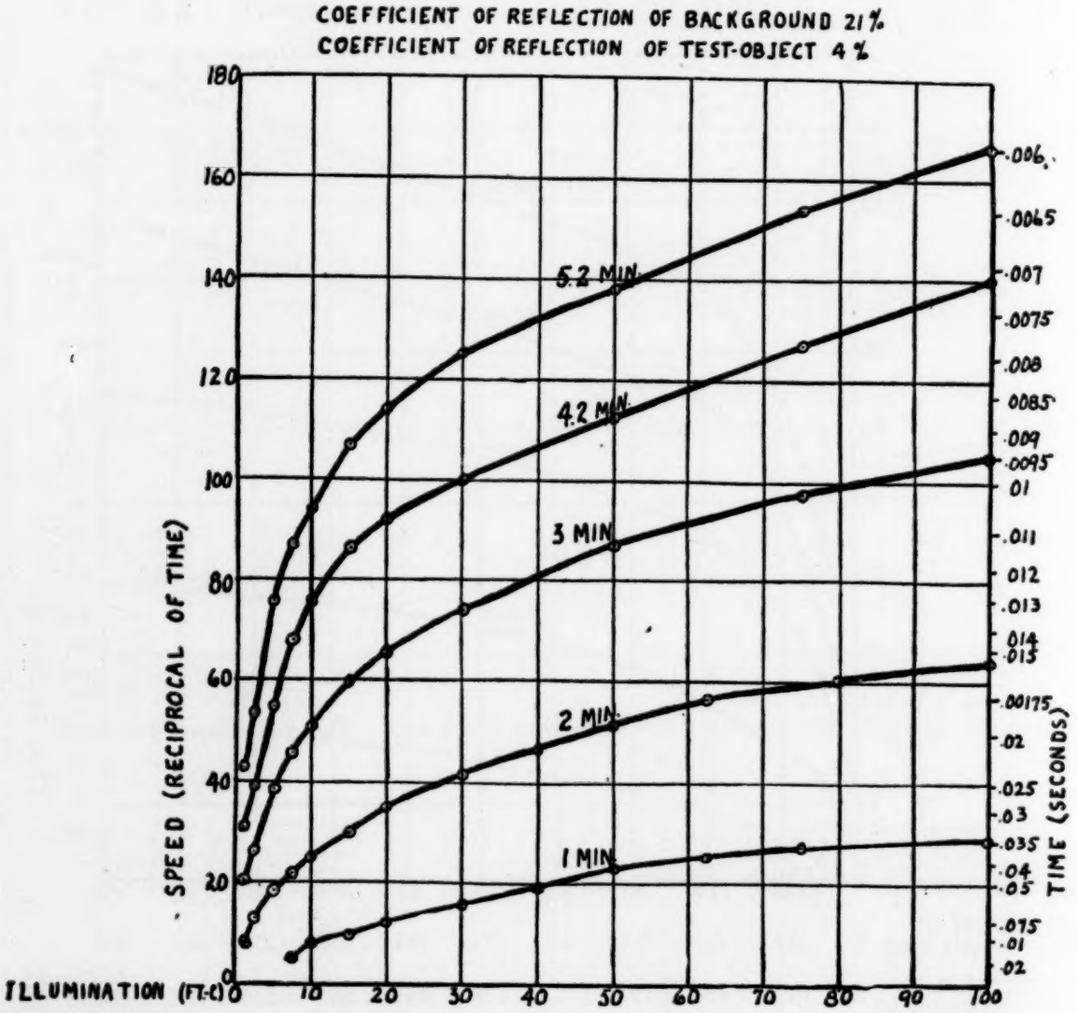
COEFFICIENT OF REFLECTION OF BACKGROUND 21%
COEFFICIENT OF REFLECTION OF TEST-OBJECT 4%
SPEED (RECIPROCAL OF TIME)
TIME (SECONDS)
5.2 MIN.
4.2 MIN.
3 MIN.
2 MIN.
1 MIN.
ILLUMINATION (FT-C) 0 10 20 30 40 50 60 70 80 90 100
BRIGHTNESS OF BACKGROUND (ML) 0 2.2 4.5 6.7 8.9 11.1 13.4 15.6 17.8 20.1 22.3
BRIGHTNESS OF TEST-OBJECT (ML.) 0 0.43 0.86 1.29 1.72 2.15 2.58 3.01 3.44 3.87 4.30
DIAMETER OF PUPIL (MM.)

FIG. 4. CURVES SHOWING THE COMPARATIVE EFFECTS OF THE FIVE SIZES OF OBJECT FOR THE BACKGROUND HAVING A COEFFICIENT OF REFLECTION OF 21 PERCENT; COEFFICIENT OF REFLECTION OF OBJECT 4 PERCENT.

increasing the size of the object. Also for the ranges of size and intensity used, the effect of increase of size is much

DATA FOR CURVES IN FIG. 4. (COEFFICIENT OF REFLECTION OF BACKGROUND 21 PERCENT; OF TEST-OBJECT 4 PERCENT)

DATA FOR CURVES IN FIG. 4. (COEFFICIENT OF REFLECTION OF BACKGROUND 21 PERCENT; OF TEST-OBJECT 4 PERCENT)

Illumination (Ft.C.)	Visual Angle 1 Min		Visual Angle 2 Min		Visual Angle 3 Min		Visual Angle 4.2 Min		Visual Angle 5.2 Min	
	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)
1.25			0.121	8.3	0.050	20.0	0.03275	30.5	0.0236	42.4
2.50			0.0738	13.0	0.0382	26.2	0.0255	39.2	0.01875	53.3
5.00			0.055	18.2	0.0260	38.5	0.0181	55.3	0.01325	75.5
7.50	0.0160	6.3	0.0455	22.0	0.0218	45.9	0.01475	67.8	0.0115	87.0
10.00	0.124	8.1	0.0398	25.1	0.0196	51.0	0.01325	75.5	0.010625	94.2
15.00	0.0996	10.0	0.0333	30.0	0.0167	59.9	0.011625	86.0	0.009375	106.7
20.00	0.0813	12.3	0.0287	34.8	0.0153	65.4	0.010875	92.0	0.00875	114.3
30.00	0.0620	16.1	0.0240	41.7	0.0135	74.1	0.010	100.0	0.0080	125.0
40.00	0.0517	19.3	0.0215	46.5						
50.00	0.0455	22.0	0.0195	51.3	0.0115	87.0	0.008875	112.7	0.00725	137.9
62.50	0.0390	25.5	0.0177	56.5						
75.00	0.0367	27.3			0.01025	97.6	0.007875	127.0	0.00650	153.9
80.00			0.0166	60.2						
100.00	0.0348	28.7	0.0157	63.7	0.0095	105.3	0.007125	140.4	0.0060	166.7

DATA FOR CURVES IN FIG. 5. (COEFFICIENT OF REFLECTION OF BACKGROUND 16 PERCENT; OF TEST-OBJECT 4 PERCENT)

Illumination (Ft.C.)	Visual Angle 1 Min		Visual Angle 2 Min		Visual Angle 3 Min		Visual Angle 4.2 Min		Visual Angle 5.2 Min	
	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)	Time of discrim'n (Sec)	Speed (Recip'al of time)
1.25			0.170	5.9	0.070	14.3	0.0458	21.8	0.0349	28.7
2.50			0.117	8.6	0.0558	17.9	0.0356	28.1	0.0278	36.0
5.00			0.0846	11.8	0.0408	24.5	0.0236	42.4	0.0187	53.5
7.50			0.0645	15.5	0.0330	30.3	0.0190	52.6	0.0154	64.9
10.00	0.171	5.9	0.0538	18.6	0.0280	35.7	0.0170	58.8	0.0135	74.1
15.00	0.138	7.3	0.0452	22.1	0.02335	42.8	0.01475	67.8	0.0120	83.3
20.00	0.118	8.5	0.0393	25.5	0.0202	49.5	0.0135	74.1	0.011125	89.9
30.00	0.0908	11.0	0.0311	32.2	0.0167	59.9	0.0120	83.3	0.0100	100.0
40.00	0.0756	13.2	0.0262	38.2						
50.00	0.0641	15.6	0.0236	42.4	0.014125	70.8	0.010625	94.1	0.008875	112.7
62.50	0.0530	18.9	0.0216	46.3						
75.00	0.0493	20.3			0.0125	80.0	0.009375	106.7	0.0080	125.0
80.00			0.0197	50.8						
100.00	0.0450	22.2	0.0185	54.1	0.0115	87.0	0.00850	117.6	0.007375	135.6

greater than the effect of increase of intensity. For example, the greatest ratio of increase of speed produced by changing the size of the object under the various conditions tested was 19; while the greatest ratio produced by the increase of

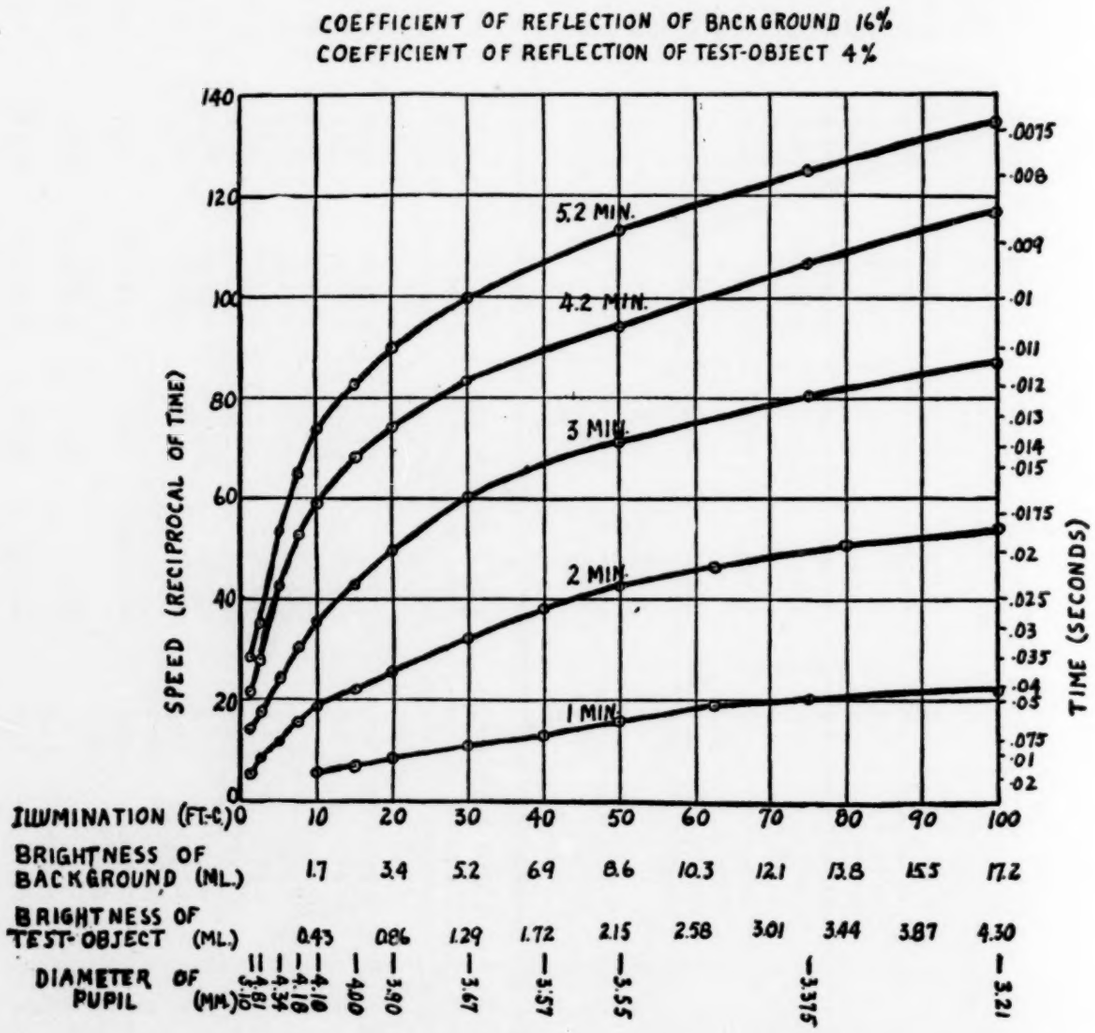

FIG. 5. CURVES SHOWING THE COMPARATIVE EFFECTS OF THE FIVE SIZES OF OBJECT FOR THE BACKGROUND HAVING A COEFFICIENT OF REFLECTION OF 16 PERCENT; COEFFICIENT OF REFLECTION OF OBJECT 4 PERCENT.

intensity was 9. Furthermore, the same speed was attained for the following combinations of size and intensity:

(*a*) 2 min visual angle at 2.5 ft.c. and
1 min visual angle at 100 ft.c.

(*b*) 5.2 min visual angle at 3.5 ft.c. and
2 min. visual angle at 100 ft.c.

(*c*) 5.2 min visual angle at 6 ft.c. and
3 min visual angle at 100 ft.c.
(*d*) 5.2 min visual angle at 30 ft.c. and
4.2 min visual angle at 100 ft.c.

The following reasons may be offered for the effect of size of object on speed of vision. (*a*) A less clear image is required for the discrimination of a large than of a small object; therefore less time is required for the adjustment of the focus. (*b*) The sensory effect develops more rapidly for a large than for a small object. And (*c*) less time is required for making the judgment. (2) The knee of the curve comes at progressively lower intensities as the size of the object is increased. With a visual angle of 1 min the knee comes at approximately 30 ft.c.; with visual angles of 2 and 3 min, at approximately 20 ft.c.; and with visual angles of 4.2 and 5.2 min, at approximately 10 ft.c. And (3) the curve becomes more sharply inflected as the size of the object is increased. This, as already stated, is due to the greater concentration of the effect of increase of intensity into the lower part of the scale, *i.e.* the curve rises more rapidly at the lower and less rapidly at the higher intensities of illumination.

These results would seem to point to the following practical conclusions. (1) There is great need for high intensities of light for the speedy discrimination of very small objects. (2) As the size of detail to be discriminated is increased there is less need of high intensities so far as speed of vision is concerned. And (3) the upper limit of the range of intensities over which the greatest benefit is obtained by increase of intensity becomes progressively lower as the size of the work is increased. In short, to use an economic expression, the point of diminishing returns is reached at a lower intensity for the large than for the small visual angles. Great care was taken in determining the location of the knee of the curve. The values on either side were checked and rechecked many times in order to make sure that the region of inflection of the curve was correctly placed.

In applying these data to practical working situations, the value of the visual angle may in any case be computed from the following formula; *tan.* ½ visual angle = $\frac{1}{2}S/D$,

in which S is taken as the size or breadth of the detail to be discriminated and D is the distance of the eye from the work. As examples of size of visual angle for well-known objects placed at the conventional reading distance from the eye 33 cm (13 in), the following may be cited:

Object	Distance viewed (cm)	Approx. value of visual angle (min)
Detail in 10-point type	33	3
Detail in 6-point type (fine print)		2
B. & S. gauge wire No. 38		1
B. & S. gauge wire No. 32		2
B. & S. gauge wire Nos. 28–29		3
B. & S. gauge wire No. 26		4
B. & S. gauge wire No. 24		5
B. & S. gauge wire No. 35	50	1
B. & S. gauge wire No. 27		2
B. & S. gauge wire No. 25		3
B. & S. gauge wire No. 23		4
B. & S. gauge wire No. 21		5
Breadth of detail of 0.145 mm	50	1
Breadth of detail of 0.290 mm		2
Breadth of detail of 0.435 mm		3

Figs. 3, 4 and 5 represent the results obtained for the five sizes of test-object when the determinations were made for backgrounds having coefficients of reflection of 29, 21 and 16 percent. These backgrounds were selected from the Hering series of gray pigment papers. As already stated, they have approximately the same coefficients of reflection respectively as polished steel and brass, unpolished steel and brass, and iron. The coefficient of reflection of the broken circle was in these cases approximately 4 percent. A 3 percent coefficient of reflection was not possible because the gray papers of the Hering series do not take printer's ink as well as the white paper. The determination for the 1-min visual angle could not be made for these backgrounds at such low intensities as formerly (1.25 ft.c.) because the threshold of discrimination for this size of object came at approximately 5 ft.c. for the lightest of the three backgrounds, at 7.5 ft.c. for the intermediate background, and at 10 ft.c. for the darkest background.

From these curves it will be noted that the speeds were not nearly so great as in Fig. 2; that a greater effect was produced by increase of intensity; also a greater effect by increase of visual angle for the lower intensities. For the higher intensities the effect of increase of visual angle was

approximately the same. The latter two points may be brought out more clearly by a computation of percentage difference.

It will be noted too that the knee of the curve comes at considerably higher intensities as the difference between the coefficient of reflection of object and background is decreased. The exact position of the knee is difficult to find. It is clear, however, that as the difference between the coefficient of reflection of object and background becomes smaller, the initial increase of speed with increase of intensity becomes less rapid and extends over a greater range, and the curves show a much less marked inflection. Under these conditions of work it would be more difficult, for example, to set a limit within the range of intensities investigated beyond which an increase of intensity would not give a justifiable return, so far as the speed of the eye's response is concerned, than it would be for backgrounds and objects having a greater difference in reflecting power.

In the following table are the approximate locations of the knee of the curve for the various backgrounds.

Background (percent)	Visual angle (min)	Intensity at which knee of curve occurs (ft.c.)
78	1	30
	2	15
	3	10–15
	4.2	10
	5.2	7.5
29	1	63
	2	35–40
	3	20
	4.2	20
	5.2	20
21	1	63
	2	40–45
	3	20–30
	4.2	20
	5.2	20
16	1	75
	2	50
	3	30
	4.2	20
	5.2	20

The Effect of Difference in Coefficient of Reflection between Object and Background. In Figs. 6, 7, 8, 9 and 10 the data

have been plotted to show more clearly the effect of difference in coefficient of reflection between object and background. In these curves a comparison is made of the effect of background for each size of object. In Figs. 6, 7 and 8 speed has been plotted on a larger scale in order to bring out more

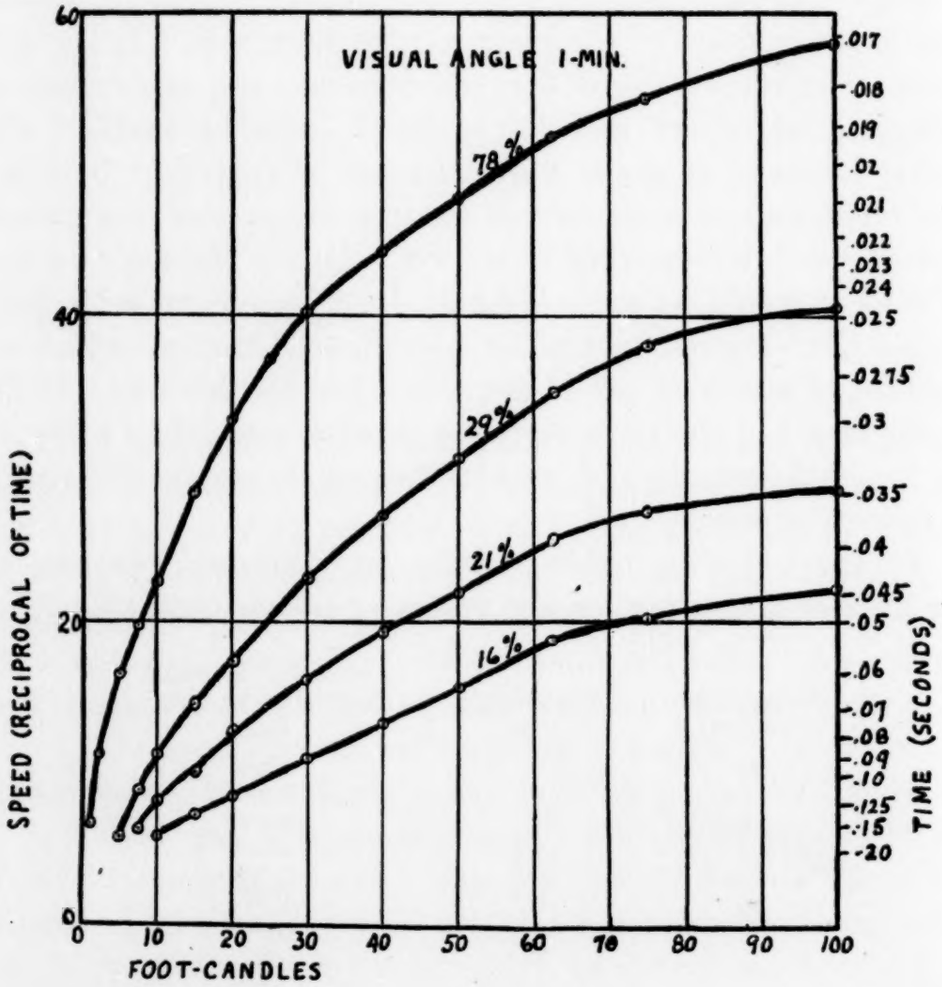

FIG. 6. CURVES SHOWING THE COMPARATIVE EFFECTS OF THE FOUR COEFFICIENTS OF REFLECTION OF BACKGROUND FOR THE OBJECT SUBTENDING A VISUAL ANGLE OF 1 MIN.

sharply the inflection of the curve for the smaller visual angles on the darker backgrounds.

It will be noted that increase of difference of coefficient of reflection between object and background has an effect very similar to that of increase of size of object; *i.e* (*a*) the speed is greatly increased for each of the conditions tested;

(*b*) the knee of the curve is shifted toward the lower end of the intensity scale, and (*c*) the curves become more sharply inflected as the difference in the coefficient of reflection is increased. The very great amount of the effect may also

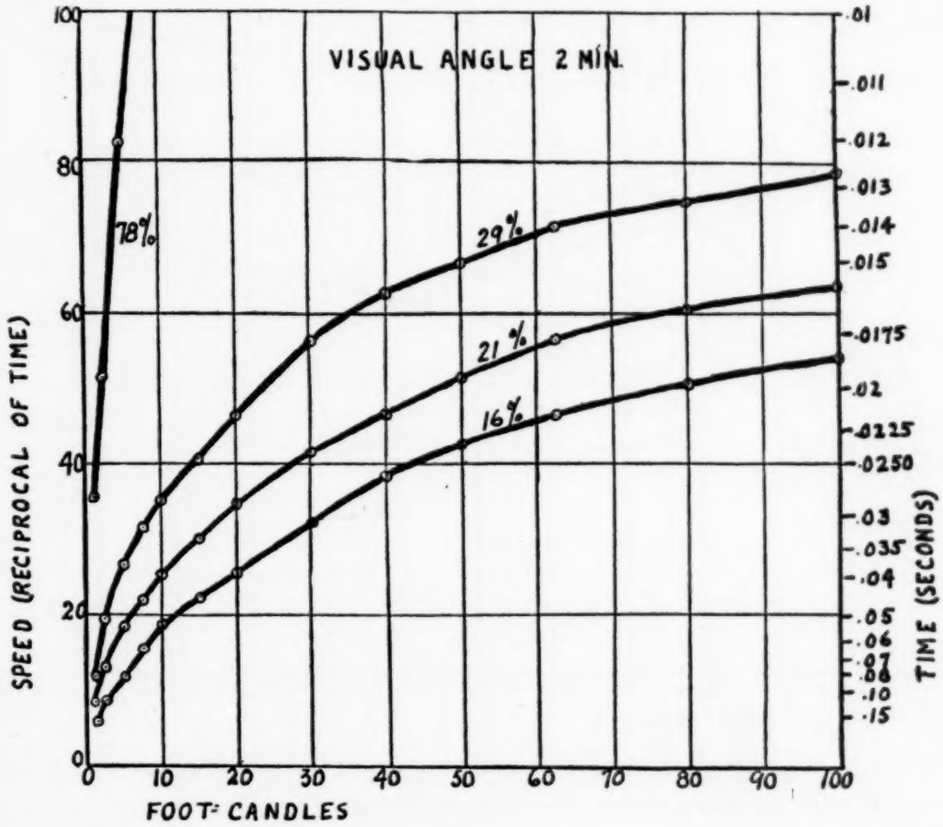

FIG. 7. CURVES SHOWING THE COMPARATIVE EFFECTS OF THE FOUR COEFFICIENTS OF REFLECTION OF BACKGROUND FOR THE OBJECT SUBTENDING A VISUAL ANGLE OF 2 MIN.

be noted. It would seem that much might be done to improve industrial conditions by giving due attention to the selection of the background against which the work is to be viewed. That, however, is not the chief reason for the consideration of the factor here. The magnitude of the effect of both size of object and difference in coefficient of reflection between object and background is emphasized in this study primarily to help make clear their very great influence on the effect of increase of intensity of light on ocular efficiency.

The question might be raised in connection with the above data whether equal speeds should not have been

expected when equal brightnesses of background were attained, whether the result were got by an appropriate combination of low coefficient of reflection and high illumi-

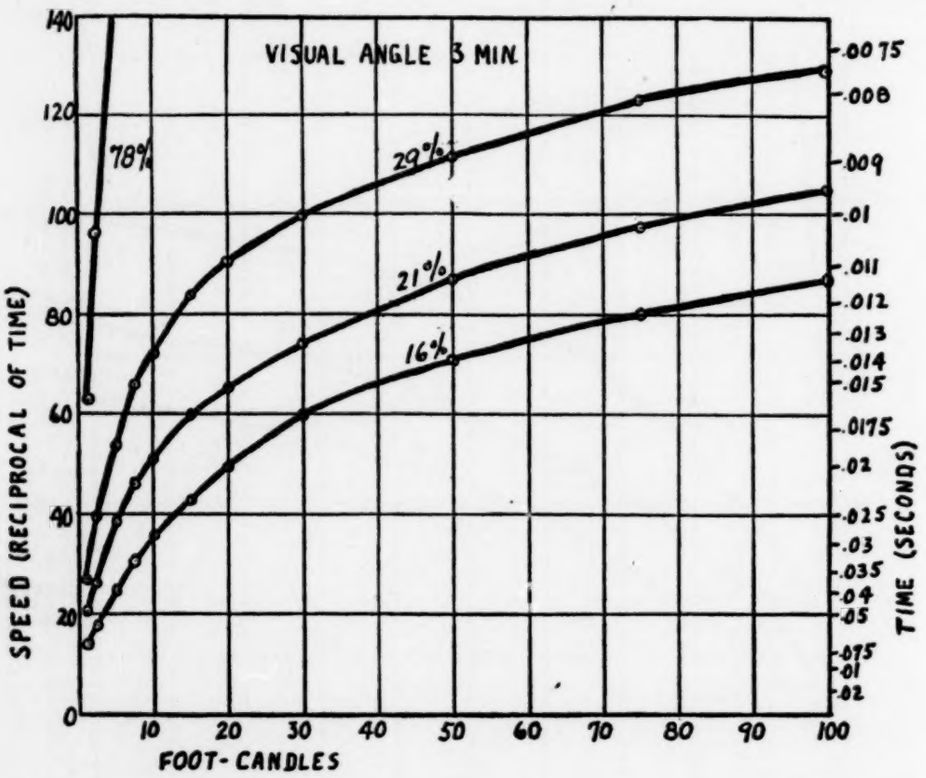

FIG. 8. CURVES SHOWING THE COMPARATIVE EFFECTS OF THE FOUR COEFFICIENTS OF REFLECTION OF BACKGROUND FOR THE OBJECT SUBTENDING A VISUAL ANGLE OF 3 MIN.

TABLE I

A COMPARISON OF THE SPEEDS OBTAINED WITH EQUAL BRIGHTNESSES OF BACKGROUND, WHICH WERE SECURED BY THE APPROPRIATE COMBINATION OF HIGH COEFFICIENT OF REFLECTION AND LOW ILLUMINATION, OR LOW COEFFICIENT OF REFLECTION AND HIGH ILLUMINATION

Coeff. of refl'n of b'kground (%)	B'ghtness of b'kground (Ml)	Illumination (Ft.C.)	Speed for Visual Angles of 1 Min	2 Min	3 Min	4.2 Min	5.2 Min
78	10	12	25	146	194	259	310
29		32	24	58	102	135	169
21		45	22	50	84	110	135
16		58	18	45	75	100	118
78	17	21	34	173	213	271	328
29		54	32	69	115	152	185
21		76	27	59	98	128	155
16		99	22	54	87	117	135

nation or the converse, high coefficient of reflection and low illumination. That the same speeds were not obtained under the two conditions is shown in Table I. From the data shown in this table it is seen that in every case a higher speed is attained with a high coefficient of reflection and a low illu-

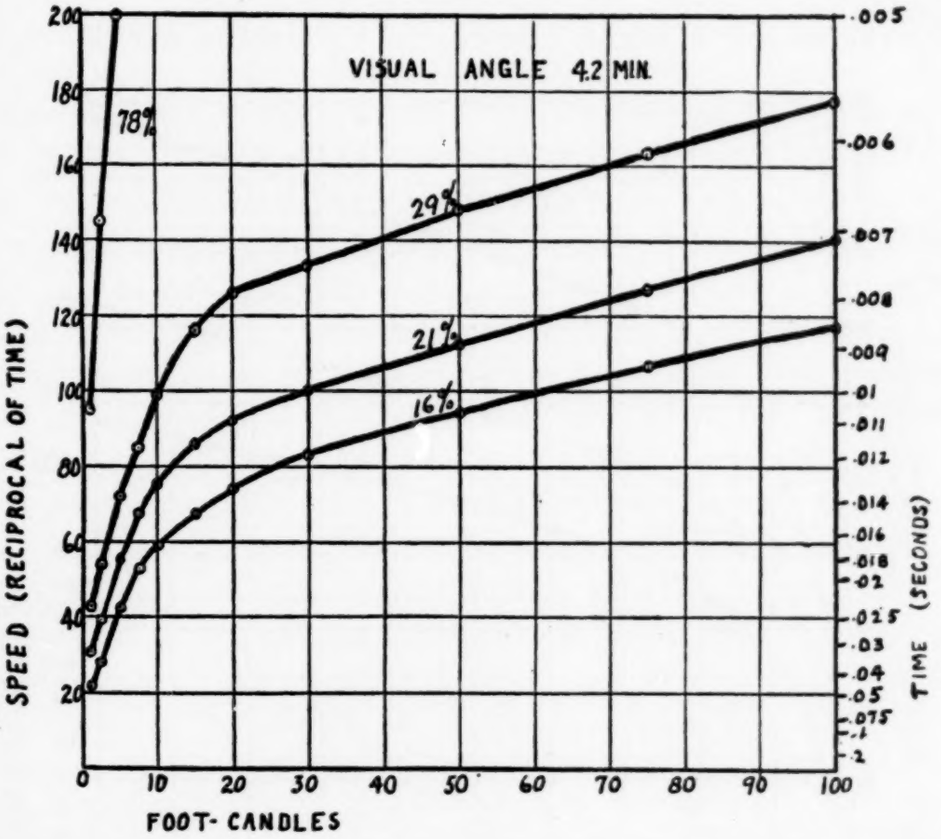

FIG. 9. CURVES SHOWING THE COMPARATIVE EFFECTS OF THE FOUR COEFFICIENTS OF REFLECTION OF BACKGROUND FOR THE OBJECT SUBTENDING A VISUAL ANGLE OF 4.2 MIN.

mination than with the equivalent brightness of background produced by a low coefficient of reflection and a high illumination.

The following reasons may be cited for this difference in result. (*a*) The eye was in a different state of adaptation when the general illumination of the room was high than when it was low. State of adaptation is an important factor in the speed of the eye's reaction. (*b*) The size of pupil was also different for a high and for a low illumination. Size of pupil is affected by other components of illumination than those coming from the object viewed. And (*c*) the prime factor in the discriminability of the object is not the brightness of the background, but the *difference* in brightness between the object and background. In the cases under discussion the coefficients

of reflection of the backgrounds were different while that of the test-object was approximately the same in all cases (3 percent for the test-object on the white background and 4 percent for the test-objects on the gray backgrounds).

Thus far the determinations have been made for a black test-object on lighter backgrounds. In a later study it is planned to reverse this relationship and to make the determinations for a white test-object on darker backgrounds.

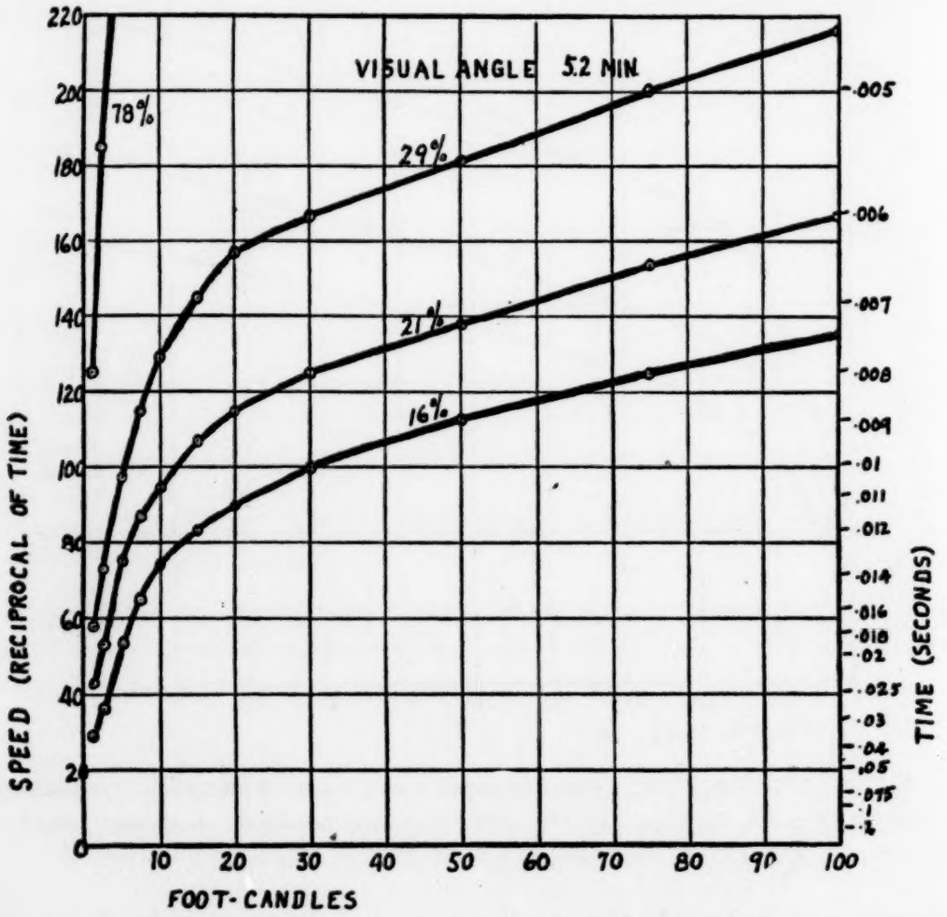

FIG. 10. CURVES SHOWING THE COMPARATIVE EFFECTS OF THE FOUR COEFFICIENTS OF REFLECTION OF BACKGROUND FOR THE OBJECT SUBTENDING A VISUAL ANGLE OF 5.2 MIN.

A commercial application for data of this kind may be found in the various textile industries where white threads are woven against backgrounds differing in brightness. There are good reasons for believing that different results will be obtained under these conditions. The apparent size of a white object on a black background is always greater than that of an

equally large black object on a white background. This is probably a phenomenon of irradiation in the image formed on the retina; *i.e.* the image of a white object by irradiation spreads or encroaches on the black background, thus becoming larger; while in case of the black object, the image of the background spreads or encroaches on the unstimulated area corresponding to the black object and renders it smaller. Again, in the present determinations the coefficients of reflection of test-object and background in three of the cases were both low. This also gives a result differing from what would be expected in case both coefficients of reflection were high, *i.e.* starting with a difference in reflection between object and background which gives an equal difference in physical brightness in the upper and lower parts of the scale, the effect of increase of intensity on the difference in sensation between the object and background is much greater in the lower than in the upper part of the scale. In order to get some idea of the amount of this difference, the following experiments were conducted. The number of just noticeable differences was determined between the sensations aroused by surfaces of 2.5 and 21.5, and of 59 and 78 percent coefficients of reflection when illuminated respectively by 0.1, 5 and 50 ft.c. of light. The results are shown in Table II. Thus we should not

TABLE II

THE NUMBER OF JUST NOTICEABLE DIFFERENCES BETWEEN THE SENSATIONS AROUSED BY SURFACES OF 2.5 AND 21.5 PERCENT AND OF 59 AND 78 PERCENT COEFFICIENT OF REFLECTION WHEN ILLUMINATED RESPECTIVELY BY 0.1, 5 AND 50 FT.C.

Illumination (Ft.C.)	Just Noticeable Differences between Surfaces of 2.5 and 21.5 Percent Coefficient of Reflection	Just Noticeable Differences between Surfaces of 59 and 78 Percent Coefficient of Reflection
0.1	47	26
5.0	83	29
50.0	132	38

Note: The determinations given in this table were made under the supervision of the authors by Katherine A. Miles, Research Assistant.

expect so great an effect of increase of intensity on speed of vision when both object and background have high as when they have low coefficients of reflection. The results in Table

II also show quantitatively why an increase in the intensity of illumination increases the discriminability of the object from its background; *i.e.* with a constant difference in coefficient of reflection of object and background, the sensation difference increases rapidly with increase of the intensity of illumination.

The Benefit of Increase of Intensity of Illumination at Various Points in the Intensity Scale. As a further aid in comparing the benefit of increase of intensity of illumination at the various points in the scale, curves have been plotted showing the percentage increase of speed for each increase of 5 ft.c. in illumination for each of the conditions tested. Whenever possible, 5 ft.c. was chosen as the illumination at which to begin the computations of percentage change. The principle employed in making the determinations was similar to that which is used in computing the Fechner fraction, *i.e.*

$$\text{Percentages} = \frac{(\text{Speed at 10 ft.c.}—\text{Speed at 5. ft.c})}{\text{Speed at 5 ft.c.}}; \quad \frac{(\text{Speed at 15 ft.c.}—\text{Speed at 10 ft.c.}); \text{ etc.}}{\text{Speed at 10 ft.c.}}$$

These curves plotted to the same scale are shown in Fig. 11. The rows from left to right in this chart show the comparison for change of visual angle; the vertical columns, the comparison for the various backgrounds. The curves show (1) that for all sizes of visual angle and all differences in coefficient of reflection the rate of increase of speed of discrimination with equal increments of illumination falls off rapidly through the lower illuminations and less rapidly at medium and high illuminations. That is to say, the maximal benefit of increase of intensity of illumination comes in the lower part of the scale for all sizes of object and all differences in the relation of coefficient of reflection for object and background. (2) The effect of increase both of size of object and of difference in coefficient of reflection between object and background is to make this rate of drop more rapid in the lower part of the intensity scale, *i.e.* the curve becomes steeper and more sharply inflected. The result is that the larger benefits of

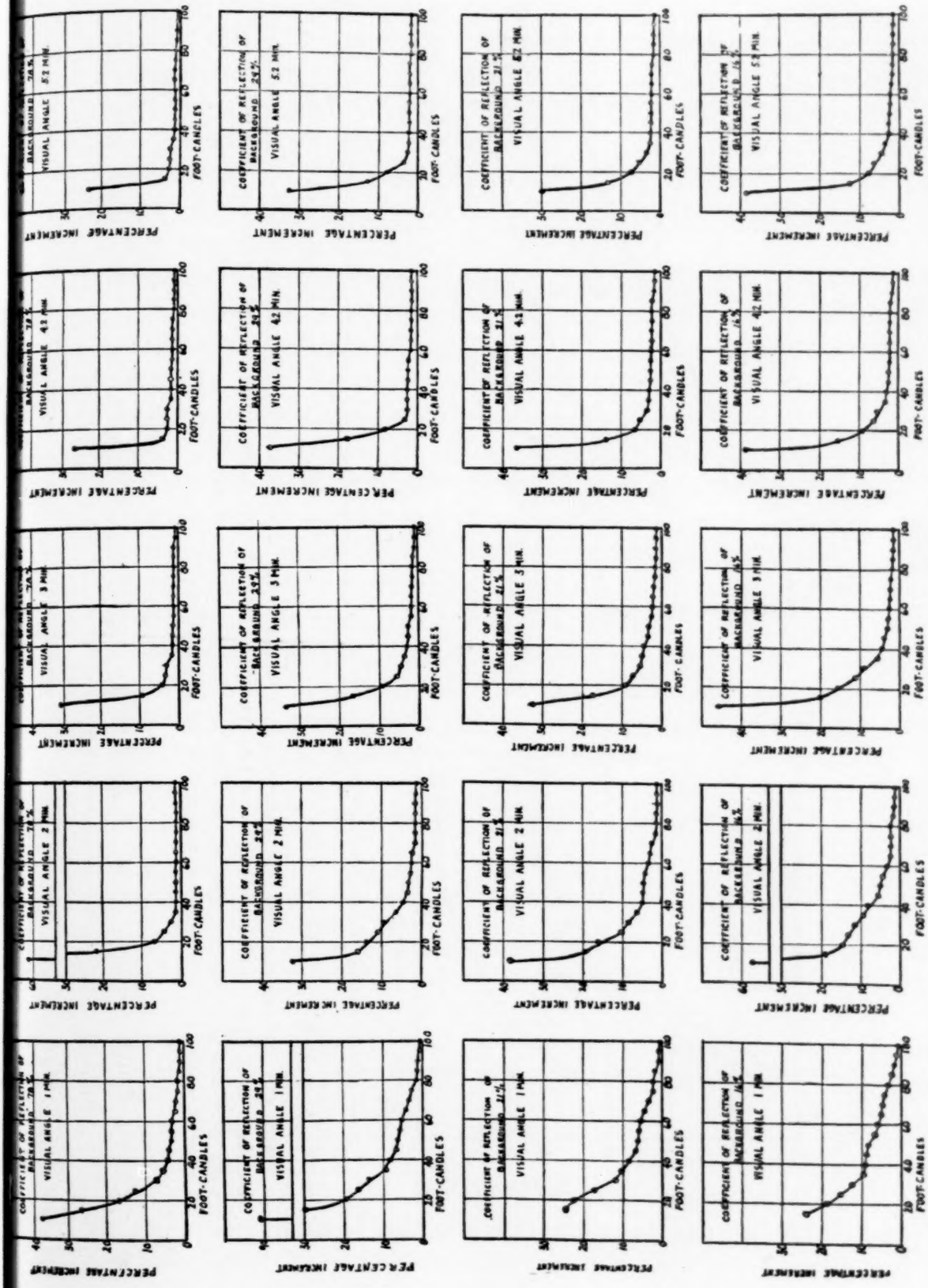

FIG. 11. CURVES SHOWING THE PERCENTAGE INCREASE OF SPEED FOR EACH INCREASE OF 5 FOOT-CANDLES IN ILLUMINATION FOR EACH OF THE CONDITIONS TESTED. THE ROWS FROM RIGHT TO LEFT SHOW THE COMPARISON FOR CHANGE OF VISUAL ANGLE; THE VERTICAL COLUMNS THE COMPARISON FOR THE DIFFERENT BACKGROUNDS.

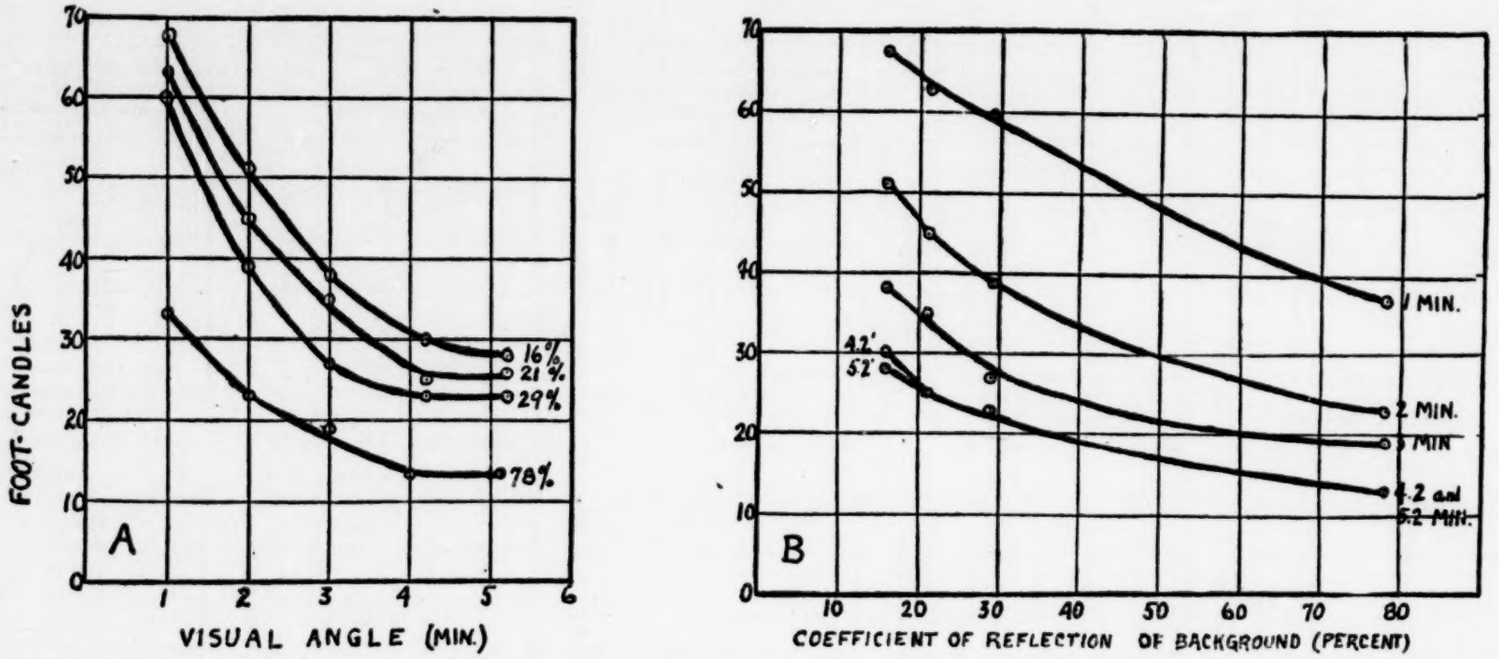

FIG. 12. CURVES SHOWING FOR EACH VISUAL ANGLE AND EACH BACKGROUND THE ILLUMINATION BELOW WHICH AN INCREASE OF 5 FT.C. PRODUCES MORE THAN 5 PERCENT, AND ABOVE WHICH AN INCREASE OF 5 FT.C. PRODUCES LESS THAN 5 PER CENT INCREASE IN SPEED OF VISION. IN CHART A FOOT-CANDLES ARE PLOTTED AGAINST MINUTES OF VISUAL ANGLE; IN CHART B AGAINST COEFFICIENT OF REFLECTION OF BACKGROUND.

increase of intensity are more narrowly limited to the lower part of the intensity scale. And (3) for all cases except the 1-min visual angle on the three backgrounds having the lower coefficients of reflection, there is a point or limited region in the scale of intensities at which the rate of increase of speed with increase of illumination becomes a constant or approximately so. This point shifts toward the lower end of the scale when either the size of visual angle or the difference in reflecting power between object and background is increased.

As a further aid to the analysis of the effect of increase of intensity on the rate of increase in speed of vision, the curves shown in Fig. 12, Charts A and B, have been plotted. In these charts are shown for each visual angle and each background the illumination below which an increase of 5 ft.c. produces more than 5 percent increase in speed of vision, and above which an increase of 5 ft.c. produces less than 5 percent increase. The curves in Chart A are intended to show the effect of size of visual angle on the location of this critical point for each background; and in Chart B, the effect of coefficient of reflection of background for each visual angle. In the former of these sets of curves, foot-candles are plotted against visual angle and, in the latter, against coefficient of reflection of background. These results are also shown in Table III.

TABLE III

SHOWING FOR EACH VISUAL ANGLE AND EACH BACKGROUND THE ILLUMINATION (ARBITRARILY CALLED CRITICAL ILLUMINATION) BELOW WHICH AN INCREASE OF 5 FT.C. PRODUCES MORE THAN 5 PERCENT AND ABOVE WHICH AN INCREASE OF 5 FT.C. PRODUCES LESS THAN 5 PERCENT INCREASE IN SPEED

Coeff. of refl'n of b'kground (%)	Critical Illuminations (ft.c.) for Visual Angles of				
	1 Min	2 Min	3 Min	4.2 Min	5.2 Min
78	37	23	19	13.5	13
29	60	39	27	23	23
21	63	45	35	25	26
16	67.5	51	38	30	28

CONCLUSIONS

(1) The effect of increase of intensity of light on the speed of the eye's response can be studied adequately only in

relation to the other factors which affect speed of vision. Probably the two most important of these factors and the two which vary most widely in different types of work are size of object and difference in coefficient of reflection between object and background.

(2) In general, the large effects of increase of intensity on the speed of discrimination occur in the lower part of the scale. Their magnitude and the range over which they occur, however, are influenced very greatly by the size of the work and the difference in coefficient of reflection from the background.

(3) The larger the work and the greater the difference in coefficient of reflection from the background, the less is the need for high intensities of illumination and the smaller is the range over which an increase of intensity may be expected to give a high return, so far as speed of vision is concerned. Under all the conditions tested, however, the benefit of increase of intensity is still present to a considerable degree at 100 ft.c. The converse of this conclusion is equally true: the smaller the work and the smaller the difference in coefficient of reflection from the background, the greater is the need for high intensities of illumination and the greater is the range over which an important benefit may be expected from increase of intensity.

(4) The point below which a 5 ft.c. increase of illumination gives more and above which it gives less than a 5-percent increase in speed of vision varies widely with the size of work and the difference in its coefficient of reflection from the background. This point, which we have arbitrarily called the critical point, shifts rapidly towards the lower end of the scale as the value of either of the above factors is increased.

(5) Among the effects of increase of size of object the following may be noted. (*a*) It greatly increases the speed of discrimination at any intensity of illumination. (*b*) It increases both absolutely and relatively the benefit of increase of intensity at the lower, and decreases it at the higher, levels of illumination. (*c*) It decreases the total percentage of benefit for the range of intensities covered in this investiga-

tion, also the range over which large returns for increase of intensity may be expected. And (*d*), within the limits chosen for these experiments, it produces much greater changes in speed of vision than are produced by changes of intensity.

(6) The effects of increase of difference in coefficient of reflection of object from background are very similar to those for increase of size of object. Within the ranges used in these experiments they are, however, not so great. From the results of related experiments it seems reasonable to expect also that with a given difference in coefficient of reflection from background, the same effect for increase of intensity will not be obtained when the object is dark and the background light as when the converse relation obtains; or when both coefficients are in the upper as when they are in the lower part of the scale.

(7) A light background and a correspondingly low illumination form a more favorable background for the discrimination of a black or dark object than a dark background and a correspondingly high illumination; *i.e.* when a given brightness of background is obtained by the appropriate combination of high coefficient of reflection and low illumination, a higher speed of discrimination is given than when it is obtained by the combination of a low coefficient of reflection and a high illumination.

(8) With a given difference in coefficient of reflection between object and background, the sensation difference increases rapidly with increase of intensity of illumination. The increase is more rapid when both object and background have a low than when they have a high coefficient of reflection. This relation of sensation difference as between object and background to intensity of illumination is an important factor in the explanation of the effect of intensity of light on the speed of discrimination.

(Manuscript received January 28, 1929)

THE COMPARATIVE RETENTION VALUES OF MAZE HABITS AND OF NONSENSE SYLLABLES

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Introduction

It is a generally accepted principle that the degree of retention is a function of the character of the material. One apparently notable illustration of this principle is afforded by a comparison of the retention of skilled acts and of verbal and informational materials. The relatively few experiments upon motor skills which have been concerned with retention as well as with acquisition have with slight exceptions agreed in finding an astonishingly high retention of these skills, even after long intervals of no, or of little, practice. With but few exceptions, likewise, the experiments upon the retention of verbal and informational materials have found these materials to be forgotten with a relatively greater rapidity, or at least the results have been so interpreted.

This seemingly large divergence between the retention of the two classes of acquired reactions has often been generalized in the statement that acts of skill are much better retained than are memorial materials. On its face, this generalization is supported by many experimental facts; but its significance is uncertain in the absence of statements specifying the conditions under which it holds, since it is fair to assume that conditions might be found under which it would not hold.

A summary of the literature will reveal the experimental evidence upon which this generalization rests and will give the experimental problem of the present paper its proper

Research Paper No. 103, Journal Series, University of Arkansas.

setting. Reference will be made only to experimental work which relates directly to the relative retention values of the two classes of materials, and particular attention will be given to retention after a seven-day interval where this interval has been used.

The writers can find in the literature no direct comparison, systematic or casual, of the retention of an act of skill with that of a section of memorial material. Any statement about relative retention values must rest, therefore, upon a comparison of results from different experiments using, perforce, different subjects and different experimental conditions. The systematic studies of the retention of skill are remarkably few, as a recent review has indicated.[1] For the greater part, the study of the retention of skill has been incidental to the study of acquisition. In the field of 'memory' material, however, retention has been more systematically investigated. In most of the 'skill' studies the scores are not presented in a manner which will permit of the computation of saving or recall scores. In discussing them, therefore, raw scores often have to be given.

The high degree of retention found in some of the earlier experiments upon skilled acts is well known. Book's[2] Subj. X made (on Jan. 16, the last day of regular practice) 1698 typing strokes in ten minutes. On June 1 he made 1365 strokes at the first test-period and at the end of ten periods had reached a score of 1472 strokes. At the first period one year later he made 1390 strokes, rising to 1850 after ten periods of practice. The losses were, then, 19.5 and 5.5 per cent. The high retention after the last interval is, of course, affected by the ten practice-periods interpolated four-months-and-a-half after the end of regular practice.

In terms of words typed per hour, Swift[3] lost about one-third of the typewriting skill acquired during practice ending two years and thirty-five days previously. In ten hours of practice he had relearned to the point originally reached by forty-five hours of practice, thus saving about 78 per cent. After an interval of 84 days, Schuyler[4] had lost about 41 percent of previously acquired typing skill. In eight days he had reached the speed with which practice closed. Freeland's[5] observations show a relatively high retention of typing habits by children, and Towne[6] found no significant change in the effectiveness of typing habits after six-and-a-half months of no practice. Bean[7] has, likewise, reported slow forgetting of typing skill.

Rejall[8] practiced typewriting a fixed paragraph and 300-word pages of new material for 114 practice-periods. He copied constant amounts, thus giving a learning curve in terms of time required. This is an improvement over the method of measuring

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[1] J. A. McGeoch, The acquisition of skill, *Psychol. Bull.*, 1927, 24, 437–466.

[2] W. F. Book, *The psychology of skill*, N. Y., Gregg, 1925 (1908).

[3] E. J. Swift, Memory of skillful movements, *Psychol. Bull.*, 1906, 3, 185–187.

[4] E. J. Swift & W. Schuyler, The learning process, *Psychol. Bull.*, 1907, 4, 307–310.

[5] G. E. Freeland, A year's study of the daily learning of six children, *Ped. Sem.*, 1921, 28, 97–115.

[6] B. M. Towne, An individual curve of learning; a study in typewriting, this JOURNAL, 1922, 5, 79–92.

[7] C. H. Bean, The curve of forgetting, *Arch. of Psychol.*, 1912, 3 (no. 21), pp. 45.

[8] L. B. Hill, A. E. Rejall, & E. L. Thorndike, Practice in the case of typewriting, *Ped. Sem.*, 1913, 20, 516–529.

amount written in a fixed time. At the close of practice his times were 2 min, 18 sec for the 100-word paragraph and 11 min, 43 sec for a 300-word page of new material. Four-and-a-half years later the times were 4 min, 52 sec and 18 min, 50 sec, respectively. Five hours of practice with new material, plus one hour with the paragraph, brought him to about the same ability to write changing material that thirty hours had been required to attain originally. Ability to write the fixed paragraph was also retained to a high degree.

In all of these experiments upon the retention of typewriting habits the degree of overlearning of large numbers of individual movements and combinations of movements must have been very high, as Thorndike [9] has indicated long since. The influence of this factor upon retention is shown in one of Bean's [10] results. When a subject practiced a list of words on the typewriter thirty times, he forgot 37.2 percent after seven days. When the initial learning was limited to twenty repetitions, 54.6 percent had been forgotten in sixty minutes. Freeland [11] also has found that unless typing has been well learned forgetting is great. While it is impossible to specify further the exact influence of various amounts of overlearning, there is little doubt that, in spite of diminishing returns, its influence upon retention is considerable.

One of Swift's [12] subjects gave, in the last six of forty-two days of practice at ball-tossing, average scores of 50, 82, 92, 88, 68, and 105. He was retested every month for five months, giving average scores of 70, 80, 140, 110, and 120. Four hundred and eighty-one days later he made an average score of 119, and four years later one of five, with rapid re-learning. A second subject, with fourteen days of practice and with retention tests every month thereafter for five months, and after 463 days, gave high scores likewise. This experiment has often been cited in support of the statement that skilled acts are very slowly forgotten. Certain facts must be noted, however, in the interpretation of these data. First, Swift's procedure favored a greater learning than the stated number of practice trials indicate, since his practice periods became progressively longer as practice continued. His criterion of a trial was tossing until a drop occurred, and as proficiency increased the trials extended, as Thorndike and Peterson [13] have pointed out. Secondly, his repeated retests were also distributed practice-periods, and the practice thus given will account for a part of the retention found after the later intervals. Thirdly, one must take account of initial proficiency after an interval, as well as of relearning. By this criterion the subject whose scores are given lost 35 points (or one-third) in the first thirty days after cessation of practice. The second subject lost 12 (127–115) points over a similar period. The scores as given are not strict measures of initial proficiency, but are averages of a day's practice during which considerable relearning must have occurred. Retention after the other intervals need not concern us here on account of the intervening practice which was present. While the retention of this habit by the two subjects is not so great as it is sometimes interpreted to be, it is nevertheless very high. One must not forget, of course, that the successful act of tossing and catching was gone through many thousands of times, thus providing opportunity for vast overlearning.

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[9] E. L. Thorndike, *Educational psychology*, vol. 2, N. Y., Teachers Coll., 1913.

[10] C. H. Bean, *op. cit.*

[11] G. E. Freeland, *op. cit.*

[12] E. J. Swift, Memory of a complex skillful act, *Amer. J. Psychol.*, 1905, 16, 131–133; Relearning a skillful act; an experimental study in neuro-muscular memory, *Psychol. Bull.*, 1910, 7, 17–19.

[13] E. L. Thorndike, *op. cit.*; J. Peterson, Experiments in ball-tossing; the significance of learning curves, this JOURNAL, 1917, 2, 178–224.

Batson[14] has continued Swift's experiments with similar procedure and results. He concludes that "there remains for long periods of time after practice ceases an ability about equal to what it was at the end of practice. In some cases it seems to increase and in nearly all cases is capable of a very rapid increase when practice is commenced again." Batson is aware that the practice periods were not equal. The subjects had a small amount of distributed casual practice between learning and relearning, which presumably affected retention favorably. Here, also, there must have been large amounts of overlearning. Braden[15] has published the results of an experiment on tossing balls at a circular hole in the top of a box. The subject practiced for 100 days, taking 200 throws per day. Twenty-two months and eleven days after practice ended a retrial of 18 days was taken, and after six months and twenty days later still a second retrial of 18 days. In the first ten trials of each section of the experiment the numbers of hits were 490, 694, and 813.

A subject of Hill's[16] practiced mirror-drawing for 48 days, one trial daily. Almost exactly three years later the subject was given eight daily trials. Comparing the end of practice with the beginning of relearning, time rose from 24 to 36 seconds and errors decreased from 24 to 18. Skill in throwing balls at a target is reported by Bean[17] to be acquired slowly and forgotten almost too slowly to provide a basis for study of the forgetting curve. Bourdon[18] has reported very slow forgetting of such activities as marking letters, naming parts of speech, and translating. A considerable retention of the ability to maintain simultaneously reading and writing activities, after an interval of more than two years, is recorded by Downey and Anderson.[19] Foucault[20] found a loss of about 25 percent, with rapid relearning, in performance with the Kraepelin addition sheets after intervals varying from thirteen to sixteen months, and Wooster[21] reports that a new spatial coördination was well-retained, "functioning at a considerable percent of effectiveness after a lapse of from one to two years." Likewise, some of Johnson's[22] subjects retained the wire-walking habit almost perfectly over one- and two-year periods. Several studies still less extensive than those cited have given results which agree with those which we have discussed.

The most systematic investigation of motor retention is that of Tsai,[23] who had groups of 16 subjects each learn the stylus-maze problem at a single sitting and relearn

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[14] W. H. Batson, Acquisition of skill, *Psychol. Monog.*, 1916, 21 (no. 91), pp. 90.

[15] S. R. Braden, An extensive experiment in motor learning and relearning, *J. Educ. Psychol.*, 1924, 15, 313–315.

[16] D. S. Hill, Minor studies in learning and relearning, *J. Educ. Psychol.*, 1914, 5, 375–386.

[17] C. H. Bean, *op. cit.*

[18] B. Bourdon, Recherches sur l'habitude, *L'Ann. psychol.*, 1901, 8, 327–340.

[19] J. E. Downey & J. E. Anderson, Retention of skill after lapse of practice; simultaneous reading and writing, *Amer. J. Psychol.*, 1917, 28, 396–408.

[20] M. Foucault, La persistance des aptitudes acquises, *L'Ann. psychol.*, 1914–19, 21, 110–118.

[21] M. Wooster, Certain factors in the development of a new spatial coördination, *Psychol. Monog.*, 1923, 32 (no. 146), pp. 96.

[22] G. B. Johnson, A study in learning to walk the tight wire, *Ped. Sem. & J. Genet. Psychol.*, 1927, 34, 118–128.

[23] C. Tsai, A comparative study of retention curves for motor habits, *Comp. Psychol. Monog.*, 1924, 2, pp. 29.

after 1, 2, 3, 5, 7 and 9 weeks, respectively. His retention values are all high. The saving percentages in terms of trials are, *e.g.* 81 after 7 days, 76 after 14 days, 66 after 21 days, and 60 after 35 days. He compares these scores with the most favorable corresponding ones from the work of Radossawljevitch, whose saving scores were 60 after 6 days, 51 after 14 days, 49 after 21 days, and 27 after 30 days. It is clear that, by this comparison, mazes are better retained than are nonsense syllables. Tsai's two recall scores gave consistently lower values than did the saving scores. Retention also varied with the criterion. Errors were above time and time above trials. A high degree of individual variability also appeared. Some subjects retained the habit almost perfectly after nine weeks, while others had lost almost all of it at the end of two weeks.

There have been at least two studies involving acts less completely motor in nature.[24] Gray has compared the retention values of substitution learning under two conditions; with the code before the subject throughout, and with four minutes of study of the code during which it could be woven into a rational system after which it was removed. After two weeks the two methods showed losses of 37.1 and 25.0 percent. Brooks had 24 subjects practice 15 minutes daily for 14 days at cancelling a's and t's, mental multiplication of three-place by two-place numbers, and inverted writing. After ten weeks of no practice the group had lost 6.37 percent of its gain in cancellation, 23.38 percent of the gain in inverted writing, and 43.12 percent of that in mental multiplication. He observes that "learning which involves the higher associative processes seems to be less permanent than that which involves a sensori-motor function."

The studies cited have agreed in finding remarkably high retention of various skills, many of them after intervals of a year or more. In the case of a few subjects, the records after an interval of no practice have even exceeded those at the close of practice. This increase does not occur, however, under entirely unambiguous conditions. In reviewing some of the papers it has been pointed out that a high degree of overlearning was present. It is probable that in all of them the learning of many of the constituent acts involved had been carried to indeterminately high points beyond the threshold. In several, likewise, varying amounts of distributed practice have occurred between the end of the regular learning period and the final measure of retention. In the case of many of the skills studied, there is no definite criterion that can be set for learning. One can only study the course of the practice curve up to a given point. In this respect the maze habit is optimal for study, since a definite

[24] C. T. Gray, A comparison of two types of learning by means of a substitution test, *J. Educ. Psychol.*, 1918, 9, 143–158; F. D. Brooks, Learning in the case of three dissimilar mental functions, this JOURNAL, 1924, 7, 462–468.

learning criterion in terms of a predetermined number of perfect trials in succession can be established.

We shall now cite a few studies of the retention of verbal and informational materials which may stand in relation to the work on the retention of skill. Here, as in the 'skill' papers, there are wide variations in technique. These variations may occur, for example, in the specific materials used, length of lists or sections, method of presentation, learning criterion, interval between learning and measurement of retention, and method of measuring retention. We can but indicate the general tendency of results obtained by varying methods.

The more significant studies of the retention of nonsense syllables after fairly long intervals are well known.[25] There have been reported percentages of forgetting after a two-day interval, for example, which vary from 27.3 to 72.2. Ebbinghaus and Radossawljevitch studied retention after longer intervals also, finding that about 80 percent had been lost after 30 days. The latter reports that about 97 percent had been forgotten after 120 days. Strong's[26] recognition curve for words gives values which come within the ranges already described. Luh has shown clearly that the degree of retention is a function of the method of measurement, however, and any exact treatment of percentages of forgetting must specify the method of measurement used, and many other factors.[27] It suffices here, however, to point out the general result that, by several diverse methods the degree of forgetting of nonsense syllables is apparently greater than the degree of forgetting of acts of skill. Tsai's comparison of his own saving-scores with the most advantageous of Radossawljevitch's results has already been cited.

Experiments with other materials have not found such large losses with the passage of time. Thorndike[28] has shown that German-English vocabularies are forgotten less readily than were the nonsense syllables in Ebbinghaus' experiment. From 40 to 50 percent of the German-English paired associates had been lost after forty days, and in a footnote Thorndike cites a similar result of Cattell's in corroboration of his own. With the implications of these results the recent results of Anderson and Jordan[29] with Latin words and phrases agree.

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[25] H. Ebbinghaus, *Memory*, (Ruger and Bussenius, tr.), N. Y., Teachers Coll., 1913, (1885); E. O. Finkenbinder, The curve of forgetting, *Amer. J. Psychol.*, 1913, 24, 8–32; C. W. Luh, The conditions of retention, *Psychol. Monog.*, 1922, 31, (no. 142), 87; P. R. Radossawljevitch, Das Behalten und Vergessen bei Kindern und Erwachsenen, Leipzig, 1907.

[26] E. K. Strong, The effect of time interval upon recognition memory, *Psychol. Rev.*, 1913, 20, 339–372.

[27] After two days, for example, the anticipation method showed a forgetting of 90 percent and the recognition method one of 28.5 percent.

[28] E. L. Thorndike, Memory for paired associates, *Psychol. Rev.*, 1908, 15, 122–138.

[29] J. P. Anderson & A. M. Jordan, Learning and retention of Latin words and phrases, *J. Educ. Psychol.*, 1928, 19, 485–496.

Dallenbach [30] finds that errors in the narrative recall of a picture increase from 10 to 22 after 45 days. When the interrogatory method is used, errors increase from 14 to 22. But his subjects benefited from two other recalls in the meantime. After five days there was an increase of but four errors by both methods of measuring recall. McGeoch and Whitely [31] have found that the retention curve for narrative reproductions of the material of the Binet object-card falls linearly to 90 days and somewhat more slowly to 120 days. After the latter interval 45.3 percent had been forgotten. In terms of answers to an interrogatory only 12.2 percent had been lost after 90 days.

Radossawljevitsch [32] reports that 50 percent of the poetry learned by his adult subjects had been lost after seven days and 76 percent after thirty days; and Ebbinghaus [33] found that poetry yielded a much greater saving than did nonsense syllables. Likewise, the results of Ebert and Meumann [34] with various materials example a much less rapid forgetting than was found by Ebbinghaus for nonsense syllables. In a recent experiment by Whitely and McGeoch [35] the retention curve for poetry falls from 64 percent after 15 days to a retention of 28 percent after 120 days, with an insignificant decrease between 30 and 90 days.

In an experiment by Henderson,[36] ideas presented in a connected and meaningful passage were relatively well retained. After two days college students had lost 25.5 percent and after twenty-eight days 31.5 percent. The averages for all the classes of subjects used were, at the two intervals, 14.7 and 25.1 percent. Words were forgotten much more rapidly than the passage. The percentage of retention of 100-word prose selections, scored in terms of the number of correct words in order, varied with Worcester's [37] subjects from 16 to 96 percent after seven days. The general tendencies run between 60 and 70 percent. Stump [38] reports that the content of a course in high school civics is lost very slowly over a 42-day interval. With this result Powers' [39] data on the retention of high school chemistry roughly agree, but Powers' data show that forgetting is very great over longer intervals.

In so far as the facts permit of comparison, these experiments show that memorial materials may, under certain conditions, be retained almost as well as are skilled acts in the

[30] K. M. Dallenbach, The relation of memory error to time interval, *Psychol. Rev.*, 1913, 20, 323–337.

[31] J. A. McGeoch & P. L. Whitely, The recall of observed material, *J. Educ. Psychol.*, 1926, 17, 419–425.

[32] P. R. Radossawljevitsch, *op. cit.*

[33] H. Ebbinghaus, *op. cit.*

[34] E. Ebert & E. Meumann, Über einige Grundfragen der Psychologie der Übungsphänomene im Bereiche des Gedächtnisses, *Arch. f. d. ges. Psychol.*, 1905, 4, 1–232.

[35] P. L. Whitely & J. A. McGeoch, The curve of retention for poetry, *J. Educ. Psychol.*, 1928, 19, 471–479.

[36] E. N. Henderson, The study of memory for connected trains of thought, *Psychol. Monog.*, 1903, 5, pp. 94.

[37] D. A. Worcester, Memory by visual and by auditory presentation, *J. Educ. Psychol.*, 1925, 16, 18–27.

[38] N. F. Stump, A class-room experiment in logical learning, *J. Appl. Psychol.*, 1927, 11, 117–124.

[39] S. R. Powers, How long do students retain what they have learned from high school chemistry? In *Contrib. to Educ.*, (J. C. Bell, ed.) vol. 1, 342–350.

experiments initially reviewed. One may even guess that, were conditions equated, there would be little difference between the retention values of the two materials.

In point, also, are a few individual cases of prolonged retention. After 46 years Titchener [40] relearned over 200 lines of Milton's *Hymn on the Morning of Christ's Nativity* in fourteen readings. Many lines were recognized either dimly or clearly. The original learning had been roughly to the threshold. Although the exact number of learning repetitions was not known, it was probably well beyond fourteen. After 22 years Ebbinghaus [41] relearned stanzas from *Don Juan* with a saving of 7 percent. After five years Worcester [42] relearned prose selections with saving scores of 43 and 44 percent. Retention tests had been made 1, 2, and 7 days after the original learning and these must have exerted a beneficial effect on retention. Nevertheless, this situation is duplicated in some of the skill experiments yielding high retention. The subject studied by Hegge [43] showed high retention for lists of varying lengths up to 350 words after ten days and one year, in spite of an obvious opportunity for retroactive influences from series learned intercurrently. This subject is possessed of supernormal memorial ability. Other facts regarding phenomenal retention may be found in the recent reviews of memory.[44]

The instances of phenomenal retention here cited have been demonstrated for single subjects in each case. In estimating their significance in connection with this problem, however, it must be remembered that the skill experiments which have yielded the most striking degrees of retention have been performed upon very few subjects. These cases of prolonged retention of poetry, prose, and words indicate, at least, that conditions exist under which such materials are retained as well as, and perhaps better than, skilled acts.

The chief experiments upon retention after long intervals of skilled acts and of memorial materials yield the following conclusions with respect to comparative retention values; (1) acts of skill, such as typewriting and ball-tossing, are retained over long periods of time with a loss, which, while small, is larger than it has often been interpreted to be, and are relearned with a large percentage of saving; (2) nonsense syllables are retained much less well than are the acts of skill reviewed, being almost completely forgotten after intervals of time over which skilled acts are still relatively well retained; (3) materials

[40] E. B. Titchener, Re-learning after forty-six years, *Amer. J. Psychol.*, 1923, 34, 468–469.

[41] H. Ebbinghaus, *Grundzüge der Psychologie*, 1911, 3d ed., vol. i, 685.

[42] D. A. Worcester, Retention after long periods, *J. Educ. Psychol.*, 1923, 14, 113–114.

[43] T. G. Hegge, Zur Analyse des Lernens mit sinnvoller Verknüpfung, *Zsch. f. Psychol.*, 1927, Erg. Bd. 13, pp. 187.

[44] E. S. Robinson, Memory, *Psychol. Bull.*, 1924, 21, 569-594; J. A. McGeoch, Memory, *ibid.*, 1928, 25, 513–549.

such as paired associates, prose, poetry, and observed data are forgotten much less slowly than are nonsense syllables, and perhaps no more rapidly than are acts of skill; and (4) certain cases of phenomenal memory show as high a degree of retention as the classical 'skill' experiments have shown.

These conclusions are the result of indirect comparisons and must be so interpreted. The 'skills' and 'memory' materials compared have been learned to vastly different degrees, under unlike conditions of distribution, presentation, and motivation. Instances of these differences have been mentioned in the discussion. Results from such experiments are directly contingent upon the experimental conditions and comparative statements are tentative and uncertain. It may be noted again, however, that one of the most outstanding and most general differences between experiments upon skill and memory has been in degree of learning, and that the present experiment attempts to equate the materials with reference to this factor.

A critical examination of experiments upon retention leads one to speculate upon the part played by review, or intercurrent practice, in producing the obtained results. During the long intervals between the learning and retention in the work of Book, Swift, Braden, Batson and others, one wonders whether the subjects did not occasionally initiate tentative or complete movements reproductive of the learned acts. Many of the subjects were deeply interested in the experiment. The significance thereof may have made it all the more difficult for them to banish it entirely when the end of practice was decreed. An occasional brief juggling of golf- or tennis-balls would be sufficient to refresh greatly the ball-tossing habit, and a description of the experiment, the sight of a typewriter or the casual observation of a typist's behavior, might reinstate in the long-practiced subject tentative reviewing movements. These are frank speculations, but they raise a very real problem. In several instances, also, it is significant that the 'retention' tests were after-thoughts, leaving no possibility that rehearsal had been guarded against.

One may assume, of course, that the chances of uncon-

trolled reinstatement are equal for skill and memory, and hence any resulting artifacts would cancel when one compares them. It seems to the writers that this is a doubtful assumption. The practice in the chief skill experiments was long-continued and must have made no small impression, as an experiment, upon the subjects, over and above the act learned. Nonsense syllables and words, whether in lists of single items or in pairs, are learned at a single sitting; they are in themselves unattractive; and there is less reason for reviewing them, either because of an oft-recalled laboratory setting or because of intrinsic motives. Behind all of the retention experiments has stalked the spectre of review, but, as we think, it has dogged skill more than memory.

Problem and Method

The problem of the present experiment is to compare the retention values of three unlike mazes with those of nonsense syllables given in lists of three different lengths. These materials have been chosen (1) because it is possible to conduct an experiment in such a way that the learning criteria are, at least nominally, equal; (2) because they yield data which can be treated in a comparable fashion; and (3) because these two types of material have given results in the past which were widely divergent, although under conditions which are far from comparable. A clean-cut difference is thus offered for analysis.[45] Great care has been exercised throughout to maintain uniform experimental conditions for the two materials in so far as the nature of the materials themselves permitted.

[45] It is recognized that there is no clear-cut difference between the materials used in 'skill' and in 'memory.' Both involve some movement and some ideation, and both may be either automatic or highly variable. It might be argued, therefore, that mazes and nonsense syllables are not really very far apart in nature as learned acts. But, the same is true for ball-tossing, typewriting, telegraphy, and similar acts, which for experimental purposes have been considered, and with valid practical grounds, to be separated from nonsense-syllable learning and similar acts by rather wide gaps. In this experiment mazes are taken to be samples of 'skill' and nonsense syllables of 'memory' material with full recognition that they are separated only relatively. The contention is that they are separated as widely as are most of the learning functions upon which the generalizations about the relative retention values of skill and memory have been based.

The mazes employed will be termed *easy*, *medium* and *hard*, the terms having significance only with reference to each other. The three mazes were designed under *a priori* considerations which were later justified by the results. Drawings of the mazes are shown in Figs. 1, 2, and 3. The

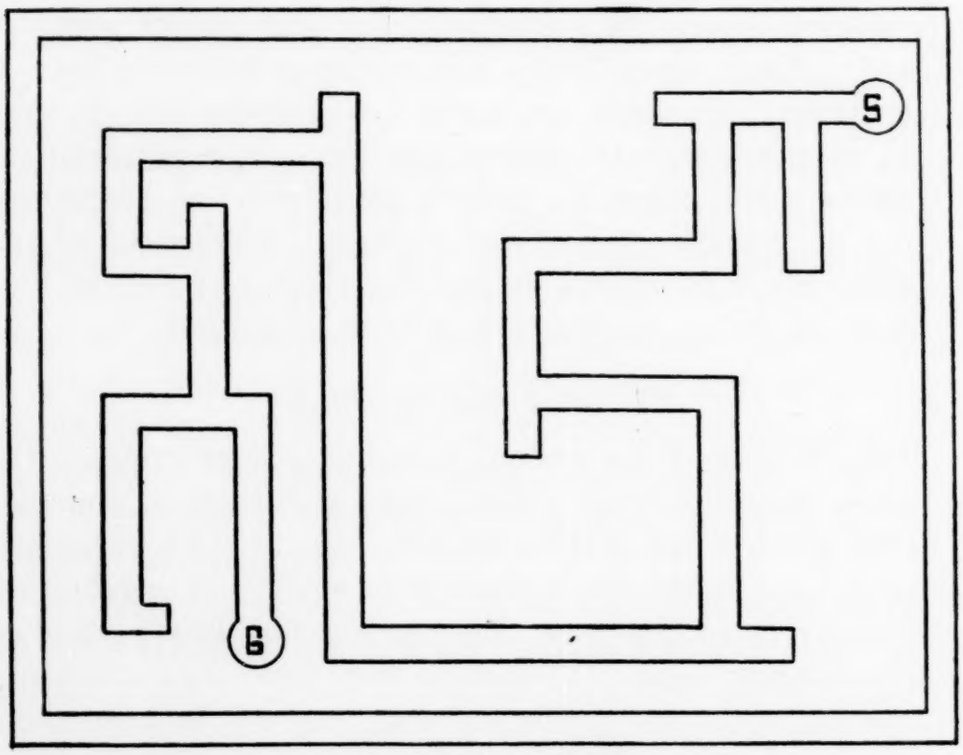

FIG. 1. Easy Maze

usual records of time, trials, and errors were taken. Entrance to any cul-de-sac section and the retracing of any section, or part thereof, of the true path, was counted as an error. Learning was by wholes with massed practice.

Lists of 8, 12 and 16 nonsense syllables were used, the same list being employed throughout at each length.[46] The lists were as follows; 8-syllable = TUS, GAK, MEB, LIX, JUV, RON, FEP, BAZ, 12-syllable = XEN, SUG, ZOR, NAD, TEC,

[46] Since the beginning of this experiment, Glaze has described the results of an experiment in which he has divided all of the syllables that can be made from the English alphabet into classes according to the percent of subjects having associations with them. (J. A. Glaze, The association value of nonsense syllables, *Ped. Sem. & J. Genet. Psychol.*, 1928, 35, 255–267.) Although our lists were constructed on the basis of our *a priori* judgments regarding their associative value, they are not, fortunately, far apart in mean associative value, as computed from the classification of each syllable in Glaze's list. The mean associative values of our lists are, 8-syllable 53.33, 12-syllable 52.22, and 16-syllable 54.44 percent.

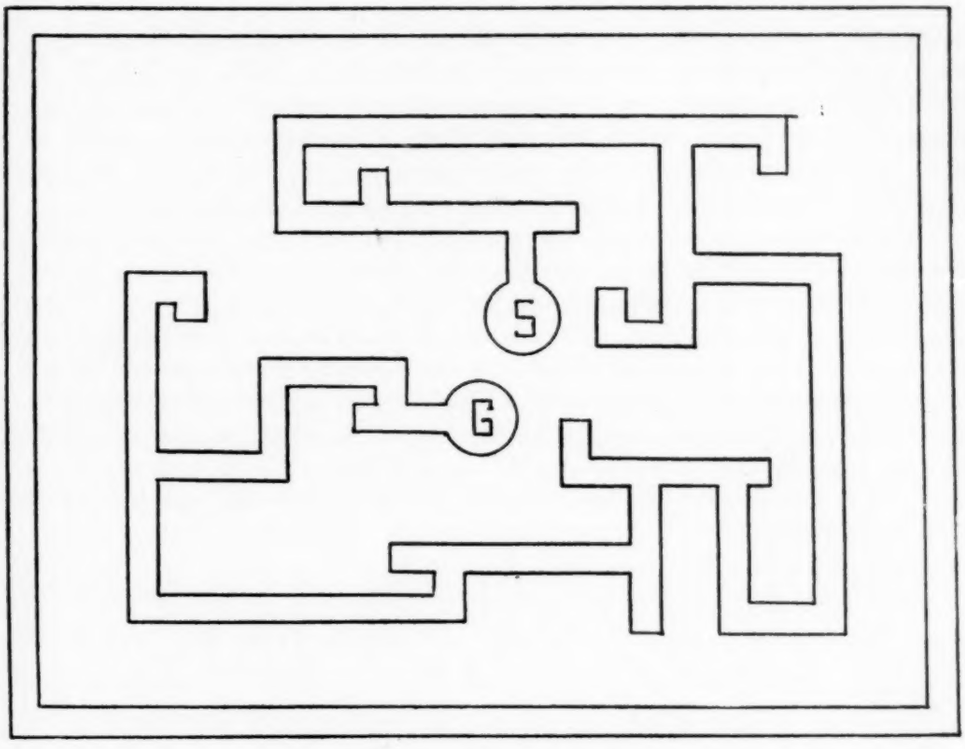

FIG. 2. Medium Maze

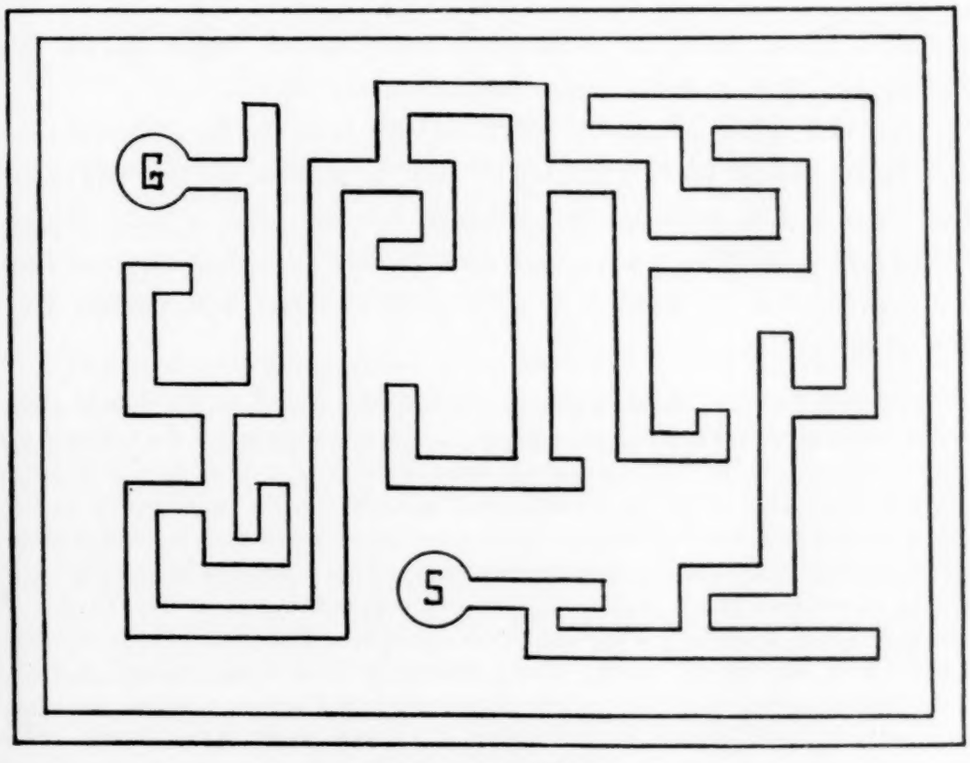

FIG. 3. Hard Maze

WUK, JIS, DAV, LOH, YEB, KIR, MUJ, and 16-syllable = FAZ, COH, WUJ, RET, GIL, KAW, PUM, SEN, XOC, LAQ, ZIR, VED, BUK, HAC, MOS, WEX. The syllables were presented at a two-second rate on a hand-operated Chicago memory drum, timed by a pendulum in full view of the experimenter but not visible to the subject. Learning was by wholes with massed practice and by the anticipation method.[47] The subject spelled the syllables and did not pronounce them.

The criterion of learning was, for the mazes, one perfect run, and for the syllables, one perfect anticipation of the complete list. This criterion brings each type of learning to a uniform, though arbitrary, threshold, and prevents any great amount of overlearning of either problem. The relative degrees of learning involved in the bringing of the two types of material to this uniform criterion are unknown and there is no known methodology for equating them. The best procedure has seemed to be to use an arbitrary, but identical, criterion for both materials, which permits us to say that they are equal in at least one significant characteristic. This at least gives a much more closely similar degree of learning than can be found in any comparisons which the literature affords.

Each subject relearned both mazes and nonsense syllables one week after the learning. In each case the relearning criterion was three perfect trials in succession. Occasionally sickness or some other occurrence prevented the return of a subject after exactly seven days. If, however, a subject delayed more than one day after the time set, all of his records were discarded and he was dropped from the experiment. Each subject who relearned after eight days was balanced by one who relearned after six days.

At the end of each learning period, each subject was carefully asked to refrain from any rehearsal of the material, and upon his return for relearning he was asked if any rehearsal had occurred. All of the records of those subjects who admitted rehearsal in any part of the experiment were discarded.

Probably the most elusive factor in any retention experiment is that of review. One is never sure that it has been controlled. In this experiment the subjects were fairly well known to the experimenter and some estimate of their honesty of intention, over and above their verbal statements, could be made. If the experimenter had any reason to doubt a subject's honesty, the results of that subject were discarded, regardless of his statements that he had not rehearsed. This procedure involves a certain amount of selection of subjects on the part of the experimenter; but it is hard to see how, in this case, it could have any significant effect, save that involved in the selection of those who had not rehearsed. Every subject knew that the relearning of each

[47] In this method the first syllable of a list serves as a cue but is not learned. Thus there were really 9, 13, and 17 syllables per list, but only the 8, 12, and 16 given above were learned.

material would be required, and he was impressed with the disastrous consequences for the experiment of even a momentary rehearsal. He was told that, if any recall occurred, he should immediately think of something else. The students received no credit of any kind for serving as subjects and an admission of review had no consequences for them save relief from further service in that experiment. Not enough of the subjects admitted review to give any ground for suspicion that this was being used as a device for gaining relief from serving. We believe that errors resulting from review are at a minimum, although beyond the safeguards described this belief is of the order of pious hope. No known device for removing this error has, however, been neglected.

Twenty-four subjects, twelve men and twelve women, all college sophomores and juniors without previous experience in learning mazes or nonsense syllables, went through the complete experiment, which required seven experimental sittings, one week apart, for each subject. At the first sitting the subject learned one maze or one syllable list. After seven days he relearned this material and learned one example of the other type of material, and so on. Thus, at any given sitting except the first and last the subject recalled a previously learned maze or list and learned a new list or maze. The conditions were counterbalanced so that each maze and each list had equal mean positions in the series. The subgroups were equated in sex.

Every subject learned and relearned in the same room, seated in the same chair, before the same table, with the same environing articles of apparatus and furniture and, save in a few instances, with the same experimenter and at the same time of day. There are, in so far as we are able to judge, no significant uncontrolled factors extraneous to the experimental conditions, save the great and constant factors of intercurrent experience and the passage of time.

The following methods of treating the comparative retention data have been employed. (1) Saving-scores have been found for trials (omitting all criterial trials), time and errors up to one perfect and to three perfect runs, treating failures to anticipate as errors in syllable learning. There is no time score in learning nonsense syllables by the anticipation method, except that obtained by multiplying the number of trials by the total exposure time per trial. This will give the same saving-score as will trials. (2) Recall scores have been computed in terms of the errors made on the first relearning trial divided by those made on the first learning trial. When

this result is multiplied by 100 and then subtracted from 100, we have a pseudo-saving score in which only the initial trials enter. We shall designate this Recall Score I. (3) Recall Score II is obtained as in (2) save that the first three trials in learning and relearning are included, instead of the first trial only.

Results

The mean learning and relearning scores are given in Tables I and II. Each number is the mean of the records of 24 subjects.[48] The time scores are in seconds. Relearning scores are to the criterion of three perfect trials.

Table I

MAZE SCORES

	Easy Maze		Medium Maze		Hard Maze	
	Learning	Relearning	Learning	Relearning	Learning	Relearning
Trials.....	11.58	13.70	19.20	19.00	32.50	36.20
Time.....	343.95	237.33	788.62	405.20	1612.75	716.81
Errors.....	96.41	38.12	314.29	73.83	767.83	176.66

Table II

NONSENSE SYLLABLE SCORES

	8-syllable		12-syllable		16-syllable	
	Learning	Relearning	Learning	Relearning	Learning	Relearning
Trials.....	12.83	7.29	22.08	14.37	28.79	14.58
Errors.....	51.16	21.16	132.70	44.16	210.54	53.91

The saving-scores for both mazes and nonsense syllables are presented in Table III.

Table III

MAZE AND NONSENSE SYLLABLE SAVING SCORES

Maze and List	Trials		Time		Errors	
	Maze	N.S.	Maze	N.S.	Maze	N.S.
Easy (8-syll).....	−18.30	43.19	31.00	43.19	60.46	58.64
Medium (12-syll).....	01.05	34.91	48.62	34.91	76.51	66.72
Hard (16-syll).....	−11.38	49.35	55.56	49.35	77.00	74.39

The saving-scores in terms of trials are uniformly much higher for nonsense syllables than for mazes. There is a

[48] Most of the distributions are somewhat skewed. Medians have been computed, but, while they differ somewhat from the means in absolute amount, they do not alter the relationships involved.

small loss for two of the mazes and a large saving for each of the syllable lists, giving differences between the two types of materials which range from 33 to 67 percent. Clearly, when retention is measured by the saving method in terms of trials, nonsense syllables are much better retained than are maze habits.

The increase in the number of trials required to relearn the easy and hard mazes is an atypical result. Tsai, for example, found a saving of 81 percent after a similar interval. Tsai's learning criterion, however, was three perfect runs in succession. The difference between his findings and our own is, probably, attributable to the difference in the learning criterion used. All of our saving-scores are less than his after the same interval; but the differences are less striking in time and errors than in trials.

Since the time per trial is fixed in learning nonsense syllables by the anticipation method, the time-score is the trial score multiplied by the exposure time for the total list. This gives, of course, the same saving-score as for trials. There is, however, nothing illegitimate in its use for comparison with maze time-scores. In terms of this score, saving is greater for the 8-syllable list than for the easy maze and greater for the medium and hard mazes than for the 12- and 16-syllable lists, respectively. There is no particular reason for comparing any one maze with any one syllable list, of course. When other comparisons are made, it is seen that the easy maze has a lower saving than any of the nonsense-syllable lists. The medium maze and the 16-syllable list are roughly equal, while this maze has a higher score than either of the other syllable lists. The hard maze is higher in score than any of the syllable lists. The mean saving-scores for the three mazes and the three syllable lists are 45.06 and 42.48, respectively. We have here a situation in which one maze and one list are equal, one maze is better than any list and one maze worse than any list. Five out of nine comparisons favor the mazes. Obviously no generalization that one material is better retained than the other can be made. The comparative retention values are a function of the particular comparison made.

When error-scores are compared, the 8-syllable list has the lowest of all the maze and syllable saving-scores. The easy maze is only slightly above the 8-syllable list and is below the two other lists. The medium and hard mazes are higher than any of the nonsense syllable lists, but the differences between these two and the 16-syllable list are not large. In summary, two mazes are retained better than any syllable list, two syllable lists are retained better than one of the mazes, and one list worse than any maze. Thus, in seven out of nine comparisons the mazes excel. The mean saving-scores are 71.32 for the mazes and 66.58 for the syllables. The gross difference is not large and few of the differences between individual pairs are large. There is, however, a tendency for the mazes to be the better retained, although not by any very great amounts.

The relative positions in retention of the three maze-learning criteria or scores agree with those reported by Tsai. Errors exhibit the largest saving, time is second, and trials are a poor third. With the nonsense syllables, errors are well above trials in saving-score.

The generalization that motor habits are more readily retained than are verbal materials finds scant support under the conditions and with the materials of this experiment. Comparing mazes of three degrees of difficulty with syllable lists of three lengths, the relative retention values are a function of the learning criteria used and of the particular maze and list which are placed in comparison. With the criterion of trials, the nonsense syllables are consistently the better retained. In no single comparison do they fail to excel the mazes. When time and errors are considered as criteria, however, certain mazes are retained better than certain syllable lists, and the converse. In terms of time, five out of nine comparisons, and in terms of errors, seven out of nine comparisons, favor the mazes. Thus in more cases than not the maze habits are the better retained in terms of these criteria. But this is not equivalent to saying that the motor habits are better retained than are the verbal materials. While more comparisons favor the mazes, there are compari-

sons in which the syllables excel. The relative retention values are a function of the particular cases compared, and not of any general principle favoring the retention of motor acts. The results make very probable the assumption that, within fairly easy limits, for every maze there could be found a nonsense syllable list the retention values of which would equal those of the maze under equated experimental conditions. It may be added that the number of subjects showing a saving with both materials and with each criterion has been counted. The results corroborate the conclusions drawn from the means.

In the interests of statistical assurance we shall include at this point a table showing the standard deviations of the differences between the learning and relearning scores from which the saving scores have been computed.

TABLE IV

DIFFERENCES BETWEEN LEARNING AND RELEARNING

	Mazes					
	Easy		Medium		Hard	
	D	Sigma	D	Sigma	D	Sigma
Trials	2.12	2.88	.20	3.70	3.70	8.94
Time	106.62	94.99	383.42	101.24	895.94	198.50
Errors	58.29	25.50	240.46	54.04	591.17	99.41
	Nonsense Syllable Lists					
	8-syllable		12-syllable		16-syllable	
Trials	5.54	1.19	7.71	1.84	14.21	3.01
Errors	30.00	4.43	88.54	9.60	156.63	21.91

The sigmas of the differences lend little added significance to the conclusions. The differences between learning and relearning trials with the mazes are highly unreliable, while those between nonsense syllable trials are statistically valid. This affects the interpretation already given only in that the amounts and probably the direction of the saving-scores for the mazes might be expected to alter considerably in other samplings. There is no indication that the consistent superiority of the syllable lists would be significantly affected.

The differences between error scores are, likewise, more reliable with the nonsense syllables than with the mazes. Except for the easy maze, however, the differences in error scores, and in time scores as well, are more than three times their standard deviations. Other samplings might alter the relationships between the saving-scores for mazes and syllables in minor respects, but there is no indication that the general implications of the results would be affected.

It is worth while to inquire, also, what the relative retention values of the two materials would be if a relearning cri-

terion which is identical with the learning criterion were applied. Hence the relearning data up to the first perfect relearning trial have been treated separately. These appear in Table V.

TABLE V

LEARNING RECORDS TO FIRST PERFECT TRIAL ONLY

	Means					
	Maze			Nonsense Syllable List		
	Easy	Medium	Hard	8-syllable	12-syllable	16-syllable
Trials	5.66	8.54	14.42	5.17	9.00	9.40
Time	127.50	210.50	384.90			
Errors	28.80	52.50	117.50	19.29	37.37	47.08
	Saving-Scores					
Trials	51.12	55.52	55.63	59.70	59.23	67.34
Time	62.66	73.30	76.13			
Errors	70.12	83.29	84.69	62.29	71.83	77.68

With a relearning criterion of one perfect trial instead of three the saving scores are uniformly higher. As regards saving in trials the mazes and the syllables come much closer together. Each list still excels every maze, however. The mean saving-scores are 54.09 and 62.09. In terms of time the 16-syllable list is better retained than the easy maze, while the two other mazes excel all syllable lists. The mean scores are 70.69 and 62.09. In terms of errors the 12- and 16-syllable lists are better than the easy maze and the two other mazes excel all syllable lists. The mean scores are 79.36 and 70.60.

Summarizing these results, in terms of saving in trials nine out of nine comparisons favor the syllables; in terms of time eight out of nine comparisons favor the mazes; and in terms of errors seven out of nine comparisons favor the mazes. Thus, when a relearning criterion of one perfect trial is used, the mazes are the better retained in a majority of the possible comparisons, except in terms of trials. The relative degree of retention is still, however, affected somewhat by the particular maze and list compared. At least one list is better, with each score, than at least one maze, and none of the differences is as large as the inference often drawn from studies of skill would lead one to expect. Few of the general implications of the results from a criterion of three perfect relearning trials are altered here.

More importance is to be attached to the results from a relearning criterion of three perfect trials because this criterion represents a more complete mastery than does a single perfect trial and we are interested in retention as represented in complete relearning. The criterion of a single perfect trial was employed in learning because it was desired to bring each material to an arbitrary threshold with as little over-learning as possible and this threshold is better represented by one than by three perfect trials.

More emphasis must be placed on saving- than on recall-scores, not necessarily because of any intrinsic advantage possessed by saving-scores, but because of the nature of the diverse temporal courses of the curves for the two materials. It is well known, and the data of this experiment agree with the general result, that a greater proportion of the total number of errors is made and eliminated in the early stages of maze learning than in the corresponding stages of syllable learning. Thus the Vincent curves for error elimination in maze learning rise sharply during about the first tenth of learning and much more slowly thereafter. The Vincent curves for syllable learning by the anticipation method are also negatively accelerated but much more gradually. Furthermore, the number of errors per trial in maze learning is indeterminate, that in syllable learning is constant at the total number of syllables in the list. This brings it about that, as a result of conditions intrinsic to the problems themselves, maze errors in the initial trials will be disproportionately large with reference to the total number of errors, while nonsense syllable errors (failures to anticipate), being limited by the number of syllables in the list, cannot vary beyond a predetermined point and do not become thus disproportionately large. Recall scores in which records in initial relearning trials are expressed as fractions of initial learning trials must inevitably show mazes to be recalled better than are syllable lists. Assume that a subject makes 1000 errors in his initial maze learning trial and 250 errors in his initial relearning trial. His recall score is 75 percent. In order to earn a recall score of 75 percent, he must recall 12 of a list of 16 syllables. One

cannot say to what extent the two scores are incomparable; but one can observe that they do not measure the same thing, because the denominators in the two cases are not obtained under comparable conditions. They would be comparable only if the possible number of maze errors was limited by the nature of the problem.

Relative recall-scores are of interest because they show to what extent the initial and final trials in the two problems are related; but they cannot be interpreted to mean that one material is intrinsically better retained than the other. In Table VI Recall Scores I and II in terms of errors are shown. The numbers in parentheses refer to the number of syllables in the list.

TABLE VI

MAZE AND SYLLABLE RECALL SCORES: ERRORS

	Maze and List					
	Easy (8)		Medium (12)		Hard (16)	
	I	II	I	II	I	II
Mazes	66.93	64.23	84.05	86.40	91.99	88.46
Syllables	15.63	33.87	19.09	38.33	23.44	42.83

Maze recall-scores are much higher throughout than are the corresponding syllable scores. This general relationship could have been predicted from the known form of the curves for the two materials. With Recall Score I the maze scores are roughly four times the syllable lists with which they are paired in the table. When Recall Score II is considered, the maze scores are about twice as large as the syllable scores with which they are paired. In no possible comparison does a syllable score approximate the magnitude of a maze score.

It can, then, be said that mazes uniformly show much higher recall values, in terms of errors, than do syllable lists; but it must be remembered that this but states a relation intrinsic to the two problems. The quantitative statement of the amount of the difference between the obtained scores and the ways in which the scores vary with the difficulty of the problem, as shown in the table, are the only experimental outcomes.

It is interesting to note that, with the error criterion,

saving- and recall-scores increase with the difficulty of the learning problem; although the criterion of learning is constant for all degrees of difficulty and length. This also holds true for maze-learning time.

For the nonsense syllable lists an overlearning ratio may be computed by the formula: 100 times the fraction, correct anticipations divided by failures to anticipate. By this formula the overlearning ratios for the 8-, 12- and 16-syllable lists are 100.6, 99.7, and 118.8, respectively. The increase in saving and recall scores is not paralleled directly by the corresponding overlearning ratios. It is probable that, with both mazes and syllables, there are factors which differ with degree of difficulty, but which are not detected in the objective records.

Summary

The retention values of mazes of three degrees of difficulty have been compared with similar values for lists of 8, 12 and 16 nonsense syllables, when each maze and each list is learned to a constant criterion of one perfect repetition. The following statements summarize our results.

1. When retention is measured in terms of saving in *trials*, the nonsense syllable lists are uniformly better retained than are the mazes. This superiority ranges from 33 to 67 percent with a criterion of three perfect relearning trials and from 3 to 16 percent with a criterion of one perfect trial.

2. When retention is measured in terms of saving in *time* (which for nonsense syllables gives scores identical with those for trials), neither learning material is uniformly superior. With the relearning criterion of three perfect trials, five out of nine possible comparisons favor the mazes; the easy maze is inferior to all the syllable lists; the medium maze and the 16-syllable list are roughly equal; the medium maze is superior to the 8- and 12-syllable lists; and the hard maze is superior to all of the syllable lists. With a relearning criterion of one perfect trial, eight out of nine comparisons favor the mazes, only the 16-syllable list excelling only the easy maze.

3. When retention is measured in terms of saving in *errors*, neither material is throughout superior. With a relearning

criterion of three perfect trials, the mazes excel in seven out of nine comparisons; the medium and hard mazes are retained better than any syllable list; the 12- and 16-syllable lists are retained better than the easy maze; and the 8-syllable list is retained less well than any maze. The gross differences, however, are not large. With a criterion of one perfect relearning trial, seven out of nine comparisons favor the mazes.

4. Recall scores, computed in terms of initial learning and relearning trials, are not comparable measures of maze and nonsense syllable retention, but have been included in the interests of completeness. By these measures the mazes are much the better recalled.

5. Although a constant learning criterion was used, the degree of retention increases with the difficulty of the problem.

6. The relative retention values of mazes and nonsense syllables are functions of the particular maze and syllable list compared, of the method by which retention is measured, and of the relearning criterion employed. In terms of trials the syllable lists are unequivocally superior. In terms of time and errors the mazes excel in a majority of the comparisons. In terms of both scores, however, at least one syllable list is equal to, or better than, at least one maze. This experiment finds, therefore, that comparative retention values vary with the specific list and maze compared, and it finds no evidence for the current generalization that motor habits are better retained than are memorial materials. Under certain conditions the mazes used are the better retained and under certain others the lists excel. When the mazes show superior retention, however, the amount of their superiority is by no means as great as that usually assigned to motor skills. The only very large difference in retention values occurs with the criterion of trials, where the syllables greatly excel the mazes. The difference between these results and those upon which the current generalization is based probably lies in the factor of degree of learning which has been, in this experiment, more nearly constant for both mazes and nonsense syllables.

(Manuscript received February 2, 1929)

RECIPROCAL INHIBITION AND REËNFORCEMENT IN THE VISUAL AND VESTIBULAR SYSTEMS

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INTRODUCTION

As has long been known, there is a reflex connection between the vestibular system and the external muscles of the eye. For example, when the head is rotated clockwise the closed eyes reflexly rotate counter-clockwise. The primary receptors under these conditions are the ampullae of the horizontal semicircular canals. Dodge (1) first secured photographic records of the various phases of these compensatory eye-movements (vestibular nystagmus) of closed eyes by using his mirror-recorder (2). He found a reflex slow phase of varying angular velocities and a cortical quick phase of approximately constant angular velocity of eye movement. The slow phase was in a direction opposed to that of the rotation of the head. The quick phase was a corrective movement which brought the eyes back towards the primary position and was in the same direction as that of rotation. The quick phase became negatively adapted after prolonged stimulation of the semicircular canals.

More recently Dodge and Fox (3) studied photographically the slow and quick phases of eye-movement during ocular pursuit of moving objects. They found that the velocity of the slow phase in adequate visual pursuit corresponds, up to certain limits (not reported), to the velocity of the moving objects. The motive for pursuit, they conjecture, would appear to be an optical impulse to hold the image of the object of regard motionless on a retinal area of relatively clear

[1] This problem is an outgrowth of the work of Professor Raymond Dodge. It was investigated in part with the coöperation of Mr. Herbert Gurnee. Some of the results were obtained during the author's tenure as National Research Fellow.

vision. The underlying mechanism of the quick phase is optic and it is due to the impulse to transfer the retinal image of a new object of relatively greater interest to an area of relatively clear vision.

The inhibiting effects of vision and of the vestibular system upon each other have been previously recorded photographically by Dodge (4) who first reported rivalry and competition between the two systems.

The problem concerned in the investigation herewith reported was the effect of vestibular stimulation on ocular pursuit and the effect of ocular pursuit on vestibular stimulation. A more definite statement of the problem in terms of experimental tasks was, first, to determine the effects of ocular pursuit of a slowly oscillating isolated object on the perception of bodily oscillation as indicated by voluntary manual response recorded on smoked paper, and, secondly, to determine the effects of vestibular stimulation by bodily oscillation on ocular pursuit of a slowly oscillating isolated object. The latter effects were secured both introspectively and from photographic records of the ocular pursuit movements.

Effects of Ocular Pursuit on Perception of Rotary Oscillation of the Body

The first experimental task involved the comparison of adequacy of voluntary response in three situations, as follows.

1. When the vestibular reflex was opposed by ocular fixation of an object moving with the body
2. When both the vestibular reflex and the ocular pursuit tended to move the eyes in the same direction and
3. When the body was oscillated and vision was excluded.

In all three situations the subject was seated at the axis of rotation with appropriate back and head supports, and responded to the perception of bodily oscillation by pressing appropriate electric keys in series with markers. Records of the response, the movements of the platform, the movements of the visual object, and the time line in seconds were obtained on the same smoked paper.

Vestibular stimulation was provided by the Dodge rotation platform which was oscillated in simple harmonic motion by a Pathé phonograph motor operating through a pulley and driving rod. This platform has been described in detail in a previous monograph by Travis and Dodge (5). The visual object was composed of seven holes arranged symmetrically at the end of an approximately light-proof tube. It was oscillated by a driving rod attached eccentrically to another pulley which was attached to the platform pulley with a chain. The visual object was illuminated and isolated in a darkened field. The seven holes, so arranged, proved to be more effective than one hole in maintaining steady fixation. The distance across the object represented approximately one degree of the visual field. An offset from the proximal end of the light-proof tube was pivoted at the axis of rotation of the platform and just above the observer's head. By suitable adjustment of the driving mechanism the platform and the distal end of the tube which carried the visual object could be oscillated in the same or opposite direction, out of phase to any degree, or either one could be held motionless while the other oscillated.

The subject was oscillated through 2 degrees at 4, 8, and 16 seconds respectively for one complete oscillation in all three situations. These times for one complete oscillation included accelerations both below and above the 50 percent threshold.

The adequacy of voluntary response to the perception of bodily oscillation in the situation with vision excluded will be taken as the standard of comparison. As is shown in Figs. 1 and 2, Curves *A* and *C*, when the visual object and body moved coincidently in the same direction, the average voluntary response for both subjects was approximately 18 percent more nearly adequate than with vision excluded. In other words, visual cues seemed to reënforce the vestibular data in the perception of bodily oscillation, in spite of the fact that the situation produced opposition between the vestibular reflex and visual pursuit. This is an illustration of neuro-muscular rivalry resulting in reënforcement in perception.

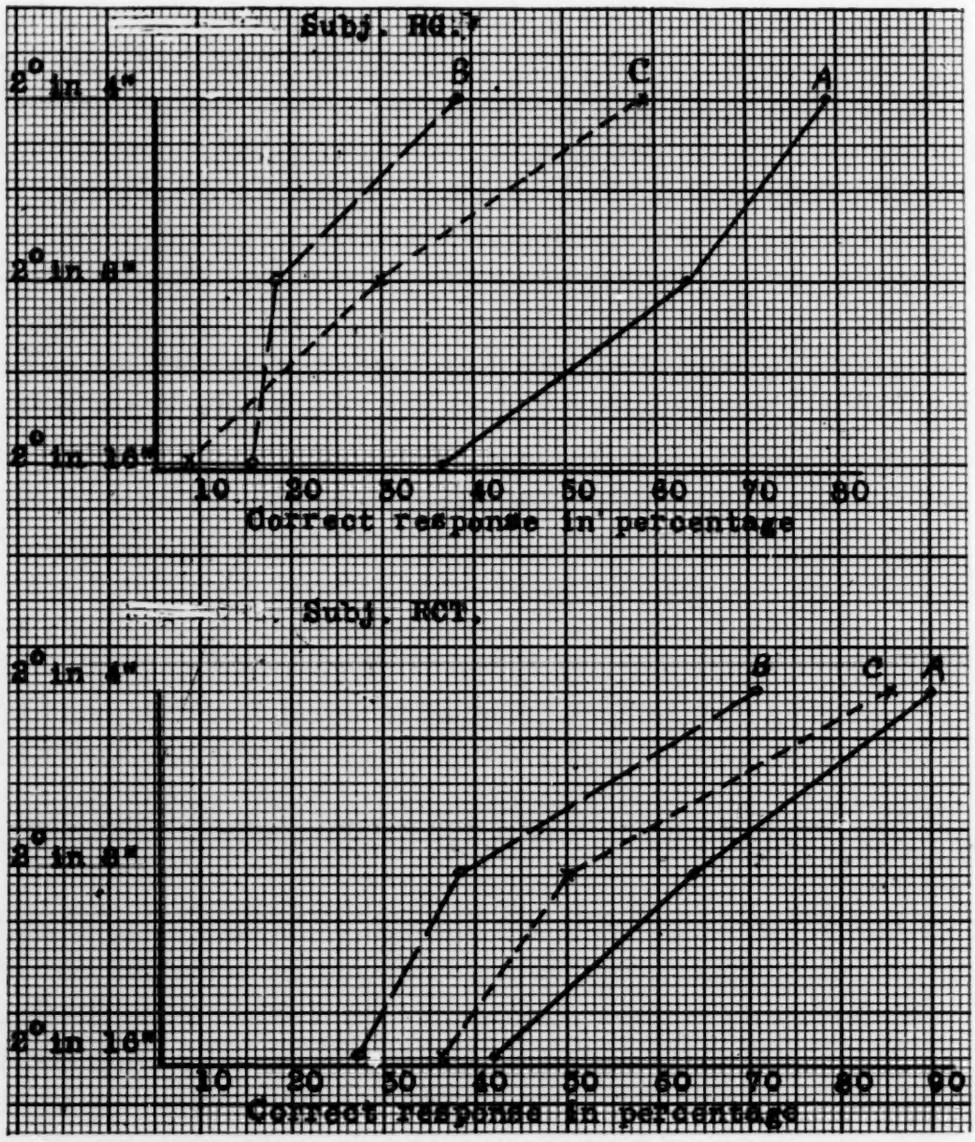

FIG. 1. Subject HG. Relation between amplitude-frequency of oscillation and adequacy of response to the perception of bodily oscillation.

Curve *A*. Voluntary response to bodily oscillation with visual object and body oscillating together.

Curve *B*. Voluntary response to bodily oscillation when visual object was stationary.

Curve *C*. Voluntary response to bodily oscillation with vision excluded.

Each point in each curve represents the average of 10 trials of 20 stimuli per trial spread over 5 days. The time of the subject's correct response to the direction of bodily movement divided by the time of actual movement gave the adequacy of response in percentage.

FIG. 2. Subject RCT. Same arrangement as in Fig. 1.

The curves *C* and *B* in Figs. 1 and 2 show that when the body oscillated and the visual object was stationary the

average voluntary response for the two subjects was 10 percent less adequate than with vision excluded. These facts are taken as evidence that the visual data partially inhibited the vestibular data in voluntary response to the perception of bodily oscillation, in spite of the fact that this experimental situation tended to produce harmony between the vestibular reflex and visual pursuit. These data illustrate neuromuscular reënforcement resulting in partial inhibition in perception. Further evidence indicates that a greater percentage of negative response occurred in the latter situation as compared with the former. This is shown in Table I.

TABLE I.

DISTRIBUTION OF NEGATIVE RESPONSE IN PERCENTAGES AT THE VARIOUS FREQUENCIES OF OSCILLATION

Amplitude	Time of one complete oscil.	Object and body oscil. together		Body oscillating Object stationary	
		Subj. HG	Subj. RCT	Subj. HG	Subj. RCT
2 deg	4 sec	3	0	24	2
2 deg	8 sec	6	8	12	16
2 deg	16 sec	15	11	23	19

THE EFFECTS OF VESTIBULAR STIMULATION ON OCULAR PURSUIT

All introspective reports accompanying the voluntary responses considered above indicated that in the first situation, when the visual object and the body oscillated together, (2 deg at 4 sec and 8 sec respectively for one complete oscillation),[2] the visual object seemed to move with the body through an arc with average estimated extent for both subjects of 5 deg, whereas the actual oscillation was only 2 deg. This seemed to indicate a reflex lapse of fixation or slight movement of the image of the visual object across the retina, which was initiated by the stimulation of the semicircular canals when the body and visual object moved together. This interpretation was proved by an increased latency, slight

[2] For the first and second situations at 2 deg at 16 sec the visual object seemed to "drift" slowly, smoothly and rhythmically first in one direction then in the other, quite independently most of the time of the stimulus rhythm. This phenomenon is important in consideration of the hypothesis that central and peripheral excitation processes interact in the initiation and control of response.

decrease in amplitude of eye movement and a greater number of corrective eye movements when they were opposed as compared to when they were in harmony, as shown in photographic records which will be discussed in the next section.

This slight reflex displacement of the retinal image in a direction opposed to the actual movement of the visual object and body must, therefore, have given the observer a definite visual cue that the object was moving in the same direction as the body. Thus the visual and vestibular cues reënforced each other in perception of motion, though the phenomenon was the reverse of that as regards the actual movement of the eyes.

In the case of the second situation, when the visual object was stationary and the body oscillated through 2 deg, the object seemed to oscillate irregularly and jerkily, but not over 2 deg and in the majority of instances much less, while it sometimes appeared to be still. It appears that the slight reflex displacement of the retinal image in this situation was in favor of the estimation that the visual object was stationary, rather than oscillating in a direction opposed to that of the body. The latter would seem to be the case if the vestibular reflex were not present. Furthermore, the vestibular reflex seemed to be unconscious since the visual object appeared to move instead of the eyes.

Assuming that the eyes remain fixed in the head and turn with it in the first situation, the visual object might, in theory, be expected to appear to remain stationary, because it moved the same distance and coincidently with the head and body, and in reference to the visual system it was fixed in space. In the second situation, on the contrary, the visual object was actually stationary and the eyes were fixed on it in pursuit, while the body oscillated. It might seem that in this situation the object should appear to oscillate regularly and rhythmically, a conjecture opposed to the facts.

The assumption that reflex, compensatory eye-movements account for the phenomena observed in the two situations has considerable evidence in its favor; but it is probably more complex than the effects of the simple interaction of the visual

and vestibular systems. The data supply evidence, in reference to perception, of the modification of the visual cortical phase by the vestibular reflex phase either when the body and visual object moved together, or when the body oscillated and the visual object remained stationary. In the first instance, it is an example of rivalry between cortical and reflex response ending in reënforcement in perception of the reflex phase; whereas, in the second instance, the result of the harmony between the vestibular reflex and ocular pursuit seemed to be reënforcement in perception of the cortical phase, in counteraction to a subjective bias in favor of the reflex phase. The problem bears directly upon the reflex initiation and cortical control of response.

Indications of Rivalry between Ocular Pursuit and the Vestibular Reflex from Photographic Records of Eye Movements

As was clear from the preliminary introspective facts and the voluntary responses, the crucial experimental measure of the rivalry between ocular pursuit and the vestibular reflex was actually to record the eye-movements under appropriate conditions. To accomplish this, the instrumental arrangement was altered to meet the new situation.

The object of pursuit was an illuminated upright slit in a vertical screen instead of the symmetrical figure of seven holes as previously used. The width of the slit represented less than 0.5 deg of the visual field. A horizontal offset at the midpoint of the vertical line tended to eliminate the accidental vertical movements of the eyes. The vertical screen carrying the slit was mounted on the moving end of an inverted pendulum which was oscillated right and left in a horizontal plane across the distal end of the dark tube. The proximal end of the dark tube was approximately 5 cm from the observer's face. A small paper tube (10 cm long and 3 cm in diameter), which lightly touched the skin around the eye, projected into the large dark tube and was held in place by the frame of the mirror recorder. It served further to eliminate distractions and extraneous light from the seeing eye.

The observer looked with the right eye through the small paper tube which projected into the dark tube, while the conjugate movements of the mechanically closed left eye were recorded by the Dodge mirror recorder (2). The beam of light reflected from the mirror fell on vertically moving sensitive paper through a horizontal slit in a recording camera which was mounted on the side of the dark tube and oscillated with the rotation platform. The roll of paper was 4 in. wide.

A lever to record the movements of the visual object was driven by the inverted pendulum and cast a shadow across the camera slit. A rigid offset from an extraneous

support also cast a shadow across the slit and served to record the movements of the rotation platform. The movements of the lever of the visual object appear as two white lines, and those of the platform as one white line on the records, whereas the curves representing the eye movements are black as shown in Fig. 3, *a*, *b*, and *c*.

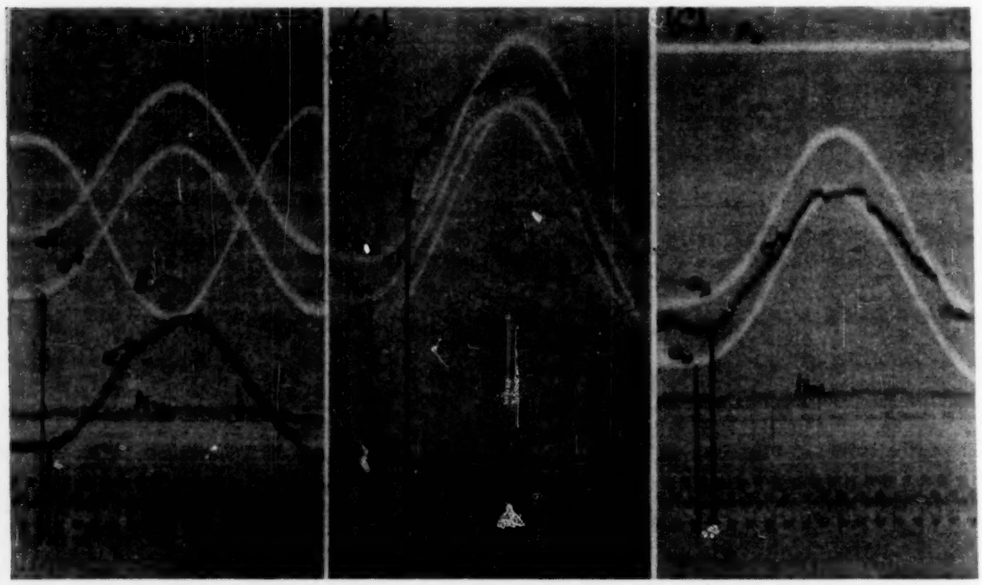

FIG. 3. Photographic records of the movements of the eye (e), platform (p), visual object (o), and the head (h).
(*a*) Visual object and platform moving in opposite directions. Reflex and pursuit in harmony.
(*b*) Visual object and platform moving in same direction. Reflex and pursuit opposed.
(*c*) Visual object oscillating, platform stationary. Reflex eliminated.
Ocular pursuit latency in each record is indicated by the vertical lines drawn through the time-lines to the curves indicating the beginning of movement of the visual object and the eye.

Clockwise movements of the eyes, the pendulum, and the platform produced counterclockwise excursions in all three recording lines. The records of both the eye and object are consequently directly comparable as to time and direction. Their respective amplitudes are not identical but are mechanically related by constants of the recording lever and the recording eye. Time in tenths-of-second was recorded by an electric marker in series with a calibrated vibrating reed. The observer was comfortably seated at the axis of rotation of the platform and was stabalized by back and head supports. The head was further held by an adjustable mouth rest. The pendulum, carrying the slit, and the platform were oscillated in harmonic motion in the same manner as described in the previous section. The object of pursuit was 75 cm from the eye. The camera was arbitrarily fixed at 60 cm from the eye, a distance which provided sufficient magnification of the eye-movements.

Records of ocular pursuit movements obtained from three experimental situations were studied, first, when ocular

pursuit was in harmony with the vestibular reflex, secondly, when ocular pursuit was antagonistic to the vestibular reflex, and thirdly, ocular pursuit of the object without the vestibular reflex. To produce harmony between the two, the rotation platform on which the subject was seated and the object of regard were oscillated through 2 deg coincidently in opposite directions. To produce antagonism, the object was oscillated 6 deg while the platform was oscillated 2 deg coincidently in the same direction. To produce the third situation the platform remained physically fixed while the object of regard oscillated 4 deg. In all three situations the object of regard oscillated through 4 deg of eye-movement at approximately 1.6 sec for one complete oscillation. The bodily oscillation through 2 deg at 1.6 sec for one complete oscillation was about double the frequency at which 90 percent of the responses to the perception of bodily oscillation with visual cues excluded were correct.

Three main characteristics of the eye-movement records will be considered in differentiating the three situations as to adequacy of ocular pursuit, namely, pursuit latency, amplitude of eye movement and the number of rapid corrective movements.

We shall first compare the pursuit latencies under the conditions of harmony and antagonism with the normal pursuit latency, *i.e.* the latency in the situation with the vestibular reflex excluded. Table II gives the average ocular pursuit latencies for each trial in the three situations for each subject. There were 11 sessions for subject C and 8 for subject H.

It is evident from Table II and Figs. 3 and 4, that the pursuit latency or the time between the beginning of the movement of the object and the beginning of the movement of the eye proved to be a conspicuous measure of the effect of the vestibular reflex on ocular pursuit. The practiced average normal latency of visual pursuit was 75 sigma for Subj. H and 111 sigma for Subj. C. When the vestibular reflex was antagonistic to pursuit the respective latencies were 129 and 163 sigma, and when the vestibular reflex was

in harmony with pursuit the respective latencies were 35 and 68 sigma for the two subjects. That is to say, when ocular pursuit was reënforced by the vestibular reflex the normal pursuit latency was decreased approximately 50 percent; but when the vestibular reflex was antagonistic to pursuit the normal pursuit latency was increased approximately 55 percent. The total averages at the bottom of Table II represent about 200 reaction times for each situation for each subject.

TABLE II

AVERAGE OCULAR PURSUIT LATENCIES FOR EACH SUBJECT FOR EACH TRIAL IN THREE SITUATIONS

Trials	Situation (1) Ocular pursuit and vestibular reflex in harmony		Situation (3) Ocular pursuit with body fixed		Situation (2) Ocular pursuit and vest. reflex antag.	
	Subj. C	Subj. H.	Subj. C	Subj. H	Subj. C	Subj. H
1	.058	.053	.116	.098	.147	.147
2	.038	.057	.136	.066	.144	.125
3	.072	.025	.113	.040	.155	.116
4	.038	.015	.106	.089	.135	.142
5	.036	.016	.089	.059	.148	.136
6	.074	.044	.111	.092	.186	.147
7	.058	.016	.074	.061	.143	.113
8	.090	.052	.131	.094	.170	.103
9	.098		.111		.182	
10	.081		.107		.191	
11	.107		.132		.190	
Average.....	.068	.035	.111	.075	.163	.129

The great decrease in the one situation and the great increase in the other situation over the normal ocular pursuit latency seems to be a very clear objective indication of the inhibiting and reënforcing effects of each system on the other in the initiation of the response.

Some variability is evident from Figs. 4 and 5 in the relative differences in the three situations from trial to trial. Dodge (6) and Miles (7) reported a lowering due to practice from trial to trial in ocular pursuit latency. A practice effect is evident in our results only in the first few trials, then there is a great deal of variation. In fact, for one subject, the latencies increased for the last few trials.

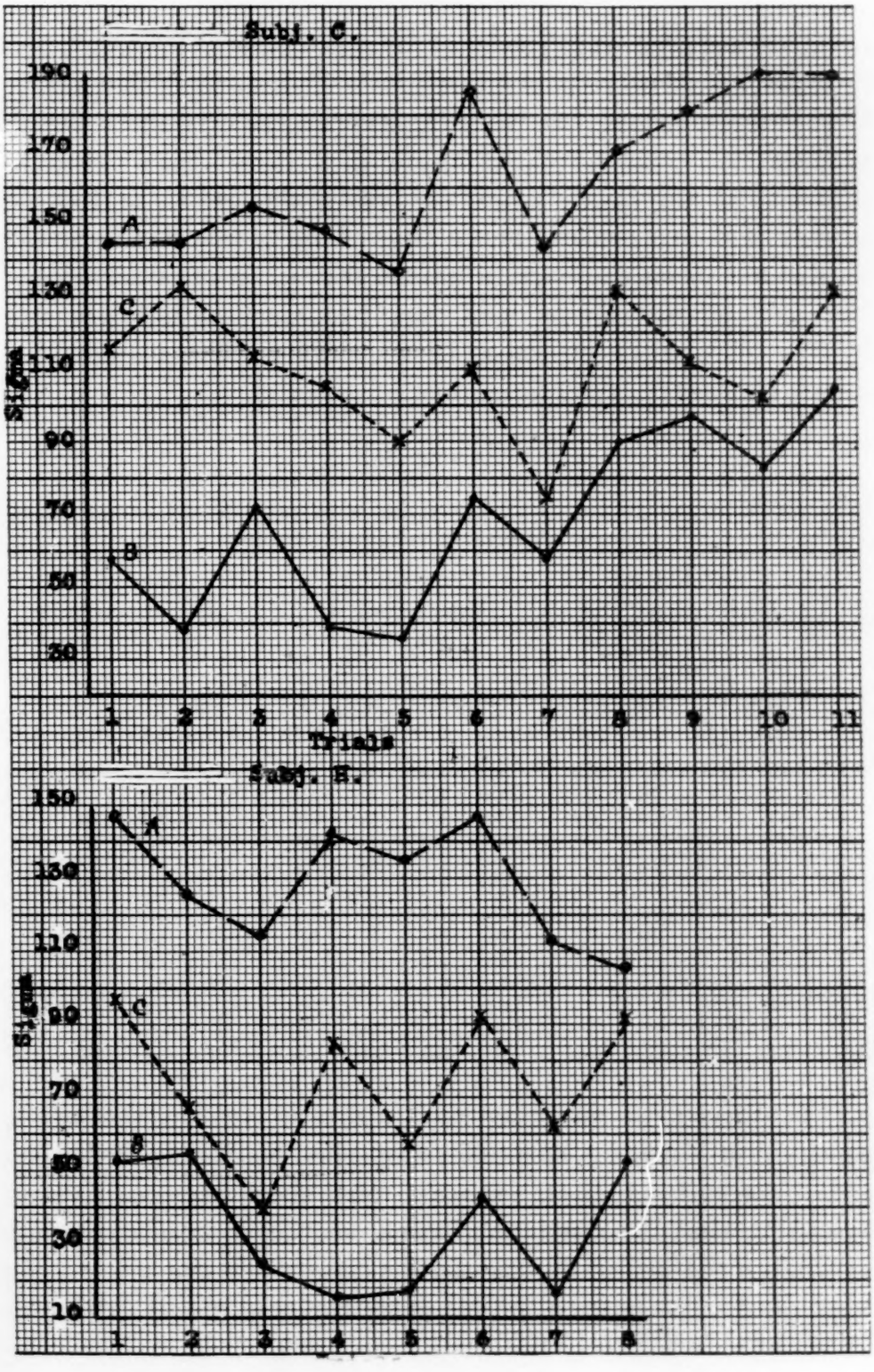

FIG. 4. Subj. C. Variation from trial to trial in ocular pursuit latency in the three situations. Ordinate given in sigma (thousandths of second).

A—Pursuit and vestibular reflex opposed

B—Pursuit and vestibular reflex in harmony

C—Pursuit with vestibular reflex excluded

FIG. 5. Subj. H. Same arrangement as in Fig. 4.

The average amplitude of eye-movement for each trial and for all three situations is given in mm in Table III for both subjects, together with the average deviations. On the face of the total averages there is a slight bias toward a diminished amplitude when the vestibular reflex and ocular pursuit are antagonistic and a slight bias in favor of increased amplitude when they are in harmony; but in consideration of the average deviations this bias becomes statistically negligible. Probably the most we can say is that a slight tendency in the two directions seemed to exist.

TABLE III

AVERAGE AMPLITUDE (IN MM) OF EYE-MOVEMENT WITH THE AVERAGE DEVIATIONS FOR BOTH SUBJECTS IN THREE SITUATIONS

Trials	Situation (1) Ocular pursuit and vestibular reflex in harmony				Situation (3) Ocular pursuit with body fixed				Situation (2) Ocular pursuit and vest. reflex opposed			
	Subj. C		Subj. H		Subj. C		Subj. H		Subj. C		Subj. H	
	Amp.	A.D.	Amp.	A.D.	Amp.	A.D.	Amp.	A.D.	Amp.	A.D.	Amp.	A.D.
1	19	1.1	27	1.5	16	1.4	26	1.8	19	2.3	25	2.0
2	14	.8	26	1.5	14	1.2	24	2.2	17	1.3	23	3.5
3	17	.8	22	1.2	16	1.5	21	2.0	13	1.6	21	1.7
4	17	1.2	24	1.2	16	1.4	23	1.5	15	1.8	22	2.1
5	16	1.2	24	1.8	15	1.4	24	2.2	14	1.3	22	1.7
6	15	1.1	20	1.3	17	1.6	19	1.2	13	2.3	18	2.2
7	21	2.0	22	1.3	21	2.5	19	1.9	14	1.6	18	2.0
8	15	1.5	20	1.7	12	0.8	18	1.7	12	1.2	18	1.3
9	14	1.1			12	0.9			11	1.5		
10	13	1.0			11	1.3			12	2.1		
11	17	2.3			15	1.2			15	1.2		
Ave.	16	1.3	23	1.4	15	1.4	22	1.8	14	1.7	21	2.1

The results in reference to amplitude are on the whole negative in showing any effect of the vestibular reflex on ocular pursuit at those speeds; but they are positive in indicating that the cortical phase involved in ocular pursuit dominates the reflex antagonistic phase after the onset. In other words, the cortical phase, after the response is initiated, controls predominately the final common path in maintaining response in accordance with ocular pursuit. We have conspicuous evidence, however, that the cortical control is subject to occasional lapses as shown by the relative number of

refixations or rapid corrective movements of the eyes in pursuit of the object in the three situations. Dodge (8) in 1907 recorded initial irregularities during pursuit of a moving pendulum.

TABLE IV

THE NUMBER OF REFIXATIONS OR CORRECTIVE EYE-MOVEMENTS AND THE CORRESPONDING NUMBER OF HALF-OSCILLATIONS OF THE MOVING OBJECT FOR TWO SUBJECTS FOR EACH TRIAL IN THREE SITUATIONS

Osc = number of half-oscillations of object
Cor = number of corrective eye movements

	Situation (1) Ocular pursuit and vestibular reflex in harmony				Situation (3) Ocular pursuit with body fixed				Situation (2) Ocular pursuit and vest. reflex opposed			
Trials	Subj. C		Subj. H		Subj. C		Subj. H		Subj. C		Subj. H	
	Osc	Cor	Osc	Cor	Osc	Cor	Osc	Cor	Osc	Cor	Osc	Cor
1	36	8	25	20	25	27	23	26	15	20	18	31
2	17	5	12	9	28	22	31	32	24	28	26	39
3	30	16	22	10	25	36	27	28	25	32	19	33
4	14	8	11	10	22	17	30	34	22	26	29	38
5	23	9	32	26	43	29	22	27	18	17	26	47
6	24	4	21	7	27	14	24	24	20	21	19	23
7	19	11	20	12	21	21	28	33	21	26	19	32
8	19	4	16	11	17	9	21	16	30	29	12	18
9	18	3			17	10			29	26		
10	7	2			7	5			7	9		
11	10	0			13	9			13	8		
Total	217	70	159	105	245	199	206	220	224	242	168	261
Percent	32		65		80		107		108		155	

Table IV gives the number of half-oscillations of the object and the corresponding number of refixational or corrective movements for each trial, for both subjects and for the three situations of ocular pursuit. For Subj. C there are 47 percent and for subject H 45 percent less corrective movements when the pursuit and vestibular reflex are in harmony than with pursuit alone. When pursuit and the reflex were opposed the number of refixating movements were 31 percent more numerous for Subj. C and 45 percent more numerous for Subj. H than with pursuit alone. These data indicate that when the vestibular reflex is in harmony with ocular pursuit the eye-movement is more nearly adequate than when the vestibular reflex is excluded. Furthermore, when the vestibular reflex is opposed to ocular pursuit a condition

is produced which results in a greater number of lapses of pursuit than with the reflex excluded.

The differences in pursuit latency and the differences in the number of rapid corrective movements seemed to be two obvious differential measures of inhibition and reënforcement in coincident stimulation of the vestibular and visual systems.

Hallucinations of Movement

The visual and vestibular systems seem to be active even though there be no immediate objective stimulus of movement. During the periods of objective stillness placed at random in the regular series of experiments, the two observers regularly perceived movement of both the body and the visual object. Hallucinatory movement of the body has been reported previously (5).

Table V gives the range and average duration in seconds of the hallucinations of movement of the body to the right and left and the duration of periods of no apparent motion.

Table V

Range and duration in seconds of hallucinatory bodily movements to the left and right and periods of no apparent movement

	During series with body and object together			During series with body oscillating; object still		
	Left	Right	No apparent movement	Left	Right	No apparent movement
Subj. HG range	3–38	1–43	1–75	1–3	1–39	1–29
Ave.	20	12	12	2	8	7
Subj. RCT range	1–39	2–29	1–34	1–32	1–29	1–17
Ave.	8	13	8	7	8	6

Table V represents averages of 20 different experimental sessions for each subject for each situation.

The apparent movements of the visual object constituted long "drifts" usually alternating in direction to the left and right with an average periodicity of approximately 60 sec for either direction. The clockwise apparent movements seemed to be longer and more intense for Subj. HG, whereas the reverse was true for Subj. RCT. The nature of these apparent movements was studied under various experimental

conditions quite at length and in detail. This material will be reported in a subsequent article.

The hallucinations of movement of the body and visual object as manifested in these two experimental situations has been described in previous reports as being a central factor possibly in conjunction with one or more peripheral factors. The central factor appears to be very closely connected with both positive and negative response and in certain instances seemed to reënforce and in others to inhibit the peripheral excitatory processes. Some times when either the visual or vestibular system was stimulated below threshold or near the threshold the central factor predominated and both the introspective report and the objective response showed a rhythm and amplitude of movement quite different and apparently independent of the objective stimulus, whether it was oscillation of the body or of the visual object.

Summary of Results

This report presents experimental data which indicated reciprocal inhibition and reënforcement in the visual and vestibular systems.

1. When ocular pursuit of an isolated oscillating object was opposed to the vestibular reflex, which was initiated by rotation of the body, the visual cues resulting from the antagonism reënforced the vestibular data as indicated introspectively and by the adequacy of voluntary manual response. When the ocular pursuit was in harmony with the vestibular reflex the resulting visual cues seemed to inhibit the vestibular data as indicated introspectively and by voluntary response.

2. The analysis of photographic records of eye movements showed outstanding differential characteristics in the three situations.

(*a*) When ocular pursuit and the vestibular reflex are in harmony the average normal pursuit latency was decreased approximately 50 percent and the number of corrective eye movements was decreased approximately 40 percent.

(*b*) When ocular pursuit and the vestibular reflex were opposed the average normal pursuit latency was increased

approximately 55 percent and the number of corrective eye movements was increased by approximately 40 percent.

(*c*) There was a tendency toward increased amplitude of eye movement when they were congruent, and toward a decreased amplitude when they were opposed. These differences in amplitude, however, were statistically negligible.

3. Hallucinations of movement both of the body and of the visual object were conspicuous in the majority of periods of physical stillness which were placed in the regular daily series of experiments.

When taken together with previous data these facts open the question as to the nature of integration of faint stimuli in the elicitation of positive and negative response. Furthermore they indicate the possibility of the operation of a central factor in conjunction with one or more peripheral excitatory processes, and the alternate predominance of one or the other under appropriate experimental conditions.

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(Manuscript received March 16, 1929)

THE INTERRELATIONS OF SPEED, ACCURACY AND DIFFICULTY

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The problem of the exact relations of speed, accuracy, and difficulty, one to another, has been attacked only incidentally until within very recent times.

The earliest work bearing upon the problem in any form seems to have been that of Fechner in 1858, using lifted weights. Increasing the time interval between stimuli increased the amount of error. Martin and Müller, Garrett, and others also have made use of lifted weights. Garrett found that there is a tendency for accuracy to increase from a low rate of lifting to medium rates and then to decrease as high rates are used, revealing an optimal rate between slowest and fastest. The same tendency was found by Henmon through the method of discrimination of linear magnitudes and by Garrett again in judging the quality of samples of handwriting. Angell and Harwood and Whipple made use of discrimination in the pitch of tones and clangs. They found a marked decrease in right judgments when the difference in tones was zero and the time interval was increased, but no regular decrease when the differences were larger. Bird with rapid and slow addition found fewer errors in rapid work. Gray, in reviewing experimental work on reading, says in summarizing upon this point that mature readers get more of the ideas from a given page by slow reading, but they get more ideas per unit of time by fast reading.

Perceptual-motor responses have been employed in some studies. Woodworth and Garrett both had subjects thrust at targets. Garrett also used maze tracing, and Woodworth used the drawing of straight lines to a certain length. In such processes it is common to find speed and accuracy inversely related; although the change in accuracy is not proportionate to the change in speed. In the case of typing Wells found a positive correlation of considerable degree between speed and accuracy.

Some studies have been concerned with the question of the constancy of relative standing in accuracy when the individuals respond at different rates. Henmon found with lifted weights that subjects who give quick judgments are neither more nor less accurate than those who respond slowly. A number of investigators—Whipple, Thorndike, Brown, Bird, and Hunsicker—have found that in the case of arithmetical computation the rapid worker tends to be accurate. Judd, King, Bird, and others found that in reading there is a similar tendency, though perhaps somewhat more variable. Freeman, Chapman, Wissler, Garrett, and others have presented results in some form which bear upon the problem of the relation of speed and accuracy from one individual to another. These results have not been entirely uniform. There is little experimental evidence relative to the effect of the degree of difficulty upon the

[1] This study is from the Psychological Laboratory of the University of Chicago and was made under the direction of Professor L. L. Thurstone.

relation of speed and accuracy; although, Fechner, Müller, Henmon, Angell and Harwood, Gray, and Whipple have given results which indicate that difficulty is a factor in determining the degree of correlation.

Results thus indicate that the relation of speed and accuracy, whether within the individual or the group, is a function of the particular activity concerned. Judgments of difference, arithmetical computation, reading, and the like are likely to show positive correlation. Perceptual-motor responses, such as thrusting at a target and maze tracing, are likely to show a negative correlation. An individual tends to keep constant at various rates his relative standing in accuracy. The relation of speed and accuracy is probably also a function of the degree of difficulty of the task.

The Problem

The present investigation has for its purpose the study of certain interrelations of speed, accuracy, and difficulty which have been more or less neglected in previous studies or which are in need of further experimental results to establish them. The following definite statement may be given to the problem.

1. Do individuals maintain at different levels of difficulty the same relative standing in speed? Is the individual who is fast at one level of difficulty also fast at other levels?

2. Do individuals maintain at various levels of difficulty the same relative standing in accuracy? Is the individual of high accuracy at one level of difficulty also of high accuracy at other levels?

3. What is the relation of speed to accuracy within the group, independent of difficulty? On the average, disregarding the degree of difficulty, does the fast individual tend to be low, average, or high in accuracy?

4. What is the relation of speed to accuracy within the group considering one level of difficulty? Does the fast individual on a task at a given level of difficulty tend to have high accuracy also at that level?

5. Does the level of difficulty affect the relation between speed and accuracy?

6. What changes occur in speed as the difficulty is increased?

The Experiment

Subjects and material. The subjects who served in the experiment were 75 undergraduate college students. Both sexes were represented in about equal numbers.

The material employed in the study was 665 spelling words selected from a variety of sources [2] to represent degrees of difficulty from very easy to very difficult. In the initial selection of the words the degree of difficulty was determined only by the opinion of the experimenter. Preliminary tests, however, were given to develop the method and to aid in the revision of the list of words. Words of two approved spellings and homonyms were avoided, though not with complete success. The words were so arranged that easy and difficult words were intermingled in random fashion. The only exception to a purely random order was that very difficult words were eliminated from the first fifteen or twenty words. This was done in order that the subjects might get somewhat adapted to the situation before encountering a difficult or strange word.

Procedure and records. The instructions, identical for all subjects, were read aloud by the experimenter, and the subject, with a second typewritten copy in hand, followed the reading. The words were presented by dictation, always in the same order, to each subject individually who wrote them at his own rate. The time was taken by means of a stop watch to fifths of a second, in the case of each word, from the end of the pronunciation of it to the completion of its spelling. The words were given in sittings of approximately one hour or less. The spelling of each subject was later scored, and the percentage of words misspelled was computed.

[2] The principal sources were the Horn-Ashbaugh Spelling Book, an unpublished list of words compiled by Mrs. Thelma Gwinn Thurstone, incidental reading, and the New International Dictionary.

Interpretation of Results

Explanation of terms. As used in this study the difficulty of a word is determined by the total number of times it was misspelled in the records of all subjects.

The accuracy record of an individual is stated in terms of the percentage of words misspelled.

The speed of a subject is expressed in the form of the average number of seconds per word required in spelling. With the scores of speed and accuracy stated in this way positive correlation coefficients between them will indicate a direct relation between speed and accuracy and negative coefficients an inverse relation.

The relative standing in speed at various levels of difficulty. Do individuals maintain the same relative speed at different levels of difficulty? In order to answer this question three lists of words were compiled from the records, one of very low difficulty, another of medium difficulty, and a third of very high difficulty. The words were so selected, too, that the average number of letters per word for the three lists is approximately the same. These three lists are referred to respectively as easy words, medium words, and difficult words. Each of these lists was then divided into two other lists such that in each case the words of the parallel lists were misspelled approximately the same number of times. That is, there were three pairs of lists of words, with 25 words in each list, and the two lists of each pair were on the average of equal difficulty.

The Pearson coefficients of correlation between standing in speed were computed for the two lists of easy words, the two lists of medium words, and the two lists of difficult words. The coefficients are measures of reliability. The coefficients for all intercorrelations were next computed. Finally, the correlation coefficients between standings in speed for the easy and the medium words, for the easy and the difficult words, and for the medium and the difficult words were corrected for attenuation. The results are shown in Table I. In this table E, M, and D represent respectively the lists of

easy, medium, and difficult words, and the subscripts refer to parallel lists.

TABLE I

CORRELATION COEFFICIENTS: SPEED WITH SPEED AT THREE LEVELS OF DIFFICULTY

Self-correlation (reliability)		Intercorrelation		Intercorrelation (corrected)	
Lists	Coef. (r)	Lists	Coef. (r)	Lists	Coef. (r)
E_1–E_2	.948	E_1–M_2	.798		
		E_2–M_1	.791	E–M	.820
M_1–M_2	.949				
		E_1–D_2	.702		
D_1–D_2	.924	E_2–D_1	.723	E–D	.762
		M_1–D_2	.904		
		M_2–D_1	.840	M–D	.936

The coefficients of reliability at the left in the table are satisfactorily high. The other coefficients, particularly those corrected for attenuation show high correlation between the relative standings in speed at different levels of difficulty, indicating that there is a strong tendency for relative speed to remain constant. This tendency, as might be expected, is more pronounced for adjacent levels than for the remote levels. The coefficient between standings in speed for easy words and for difficult words (.762) is less than either that for easy and medium words (.820) or that for medium and difficult words (.936). The higher correlation for medium and difficult words than for easy and medium words is probably due to a greater similarity between the former two situations than between the latter two. Both medium and difficult words call for a considerable degree of deliberation, while the easy words call for almost none.

In order to carry further the study of the constancy of standing in speed, eleven lists of words were formed from the records, ranging from very easy to very difficult by approximately equal steps. The easiest list is referred to as 1, and the most difficult as 11, and the other lists accordingly. The standings in speed on list 1 are correlated with standings in speed on each succeeding list. The coefficients are presented in Table II.

TABLE II

CORRELATION COEFFICIENTS: SPEED ON EASY WORDS WITH SPEED ON MORE DIFFICULT WORDS

Lists Correlated	Coefficients (r)
1–2	.936
1–3	.914
1–4	.897
1–5	.880
1–6	.859
1–7	.778
1–8	.733
1–9	.779
1–10	.749
1–11	.745

There is apparent here the same tendency that was noted in the case of words of three levels of difficulty. The lowest coefficient is .733, indicating quite a strong tendency for relative speed to remain constant. There is found also, as might be expected from the previous results, a decrease in this tendency as the lists of words correlated become further separated in degree of difficulty. There is a reversion near the end, which may mean that as the words become hopelessly difficult subjects are inclined to spell rapidly and with little thought, and so to spell under conditions more similar to those effective in the case of easy words. Certainly this tendency to spell rather quickly and somewhat carelessly the very difficult words was noticed in the case of some subjects.

In general, then, relative speed is not greatly altered at different levels of difficulty. Speed of a given degree, low or high, seems to be more or less of a constant factor in spelling in the case of an individual. The individual who is fast upon easy spelling material will likely, though not certainly, have an approximately equal standing in speed on more difficult material. Similarly, the slow individual on easy spelling material will probably be slow on material of other degrees of difficulty, and those of intermediate degrees of speed will hold approximately the same rank in speed throughout the variations in the degree of difficulty.

Relative standing in accuracy at various levels of difficulty. The question here is, Does an individual maintain the same

relative standing in accuracy at the different levels of difficulty? The same three lists of easy, medium, and difficult words described and used in the last section are employed here. Correlation coefficients were computed for the relation of standings in accuracy on the easy and the medium lists, on the easy and the difficult lists, and on the medium and the difficult lists. The coefficients are given in Table III.

TABLE III

CORRELATION COEFFICIENTS: ACCURACY WITH ACCURACY FOR THREE LEVELS OF DIFFICULTY

Lists Correlated	Coefficients (r)
E–M	.631
E–D	.414
M–D	.669

These coefficients are much smaller than the corresponding coefficients in the case of speed. An individual is not quite so likely to hold his place in accuracy as he is in speed; though the coefficients are sufficiently large to indicate a very definite tendency toward this result. A considerable change in relative standing in accuracy may be expected on difficult words. The standings with respect to medium words and difficult words are more likely to be near together. An individual of given accuracy—high, low, or average—at a given level of difficulty will be more likely than not to fall within the same general region of accuracy at other levels of difficulty. The good speller on easy words will probably be a fairly good speller on medium and difficult words. And similarly, the poor speller and average speller on easy words will probably fall within the same respective class on more difficult words.

The general relation of speed and accuracy within the group. What is the general relation of speed and accuracy within the group considered without reference to the degree of difficulty, that is, by considering this relationship for all words taken together, whether easy or difficult? Does the fast individual, all words considered, tend to be high in accuracy?

The general speed-score for each subject, that is, the

general average time per word for each subject, was correlated with his general-accuracy score stated in terms of the percentage of words misspelled. The coefficient was found to be .346. This is comparable with the coefficients reported for speed and accuracy in addition by Whipple, Brown, and Thorndike. It is sufficiently large to indicate a tendency for the fast worker to be more accurate than the slow worker in the case of spelling.

This general relation between speed and accuracy is studied further by comparisons of the accuracy of groups of individuals having different speeds. After arranging the subjects in rank order on the basis of the average time per word, they were divided into four groups as nearly equal in size as possible. The average time per word for each of the four groups and the percentage of misspelled words for each group were computed. The results are shown in Table IV.

TABLE IV

SPEED AND ACCURACY FOR GROUPS OF SUBJECTS OF DIFFERENT SPEED

Group	No. of Subj.	Av. time per word	Av. No. words misspelled	Percentage of words misspelled
1	19	3.48	161.42	24.27
2	19	3.93	168.75	25.41
3	19	4.53	175.26	26.41
4	18	5.50	211.22	31.76

This table shows again in a general way that there is a positive relation between speed and accuracy, in that as the average speed decreases (or the average time per word increases) the average accuracy also decreases. This is the same tendency indicated by the positive correlation found between speed and accuracy using the general scores with respect to these factors.

The relation of speed and accuracy within the group at the same and at unlike levels of difficulty. The questions raised here are the following: What is the degree of correlation between speed and accuracy when the degree of difficulty is taken into account? Is an individual who is fast on easy words likely to be accurate on these same easy words? Is an

individual who is fast on easy words likely to be accurate on medium and difficult words?

The correlation coefficients between speed and accuracy were computed for each of the lists of easy, medium, and difficult words. They were computed also for speed on easy words and accuracy on medium words and difficult words, and for speed on medium words and accuracy on difficult words. The coefficients found are given in Table V.

TABLE V

CORRELATION COEFFICIENTS: SPEED WITH ACCURACY AT THE SAME AND HIGHER LEVELS OF DIFFICULTY

Groups Correlated	Coefficients (r)
E–E	.631
M–M	.397
D–D	−.016
E–M	.378
E–D	.153
M–D	.265

The first three coefficients in the above table show the relation between speed and accuracy at the three levels of difficulty. They make it clear that the level of difficulty affects decidedly the degree of correlation between speed and accuracy. Allowing for the fact that the coefficient in the case of easy words is undoubtedly affected by the relatively large number of zero-accuracy scores, there is still a high degree of positive correlation between these factors for easy words, a much lower degree of correlation for medium words, and a low degree of negative correlation for difficult words. The coefficient in the last case is so small (−.016) that it may be regarded as zero. An individual does not have equal chances of the same rank in speed and accuracy at the various levels of difficulty. On easy words the chances are good that he will have about the same rank. On medium words the chance is far below that on easy words, and on difficult words nothing at all can be predicted as to standing in accuracy from standing in speed.

When relative standing in speed at one level and in

accuracy at a higher level are considered, positive coefficients are found, but none of them is high. These coefficients are the last three given in Table V. The highest coefficient is that showing the relation of these factors with respect to the easy and the medium lists. The coefficient is lowest for the easy and difficult lists.

It may be objected that the positive relation here found resides in the peculiar nature of the spelling situation and is a matter of course. If an individual is confronted by a word which he does not know how to spell or about which he is uncertain, he will, of course, take a longer time for it than for a word whose correct spelling is known, and, of course, he will be more likely to misspell the word he does not know. This is true. But after all, this is the case with respect to any task, arithmetic, discrimination of weights or lines, judging handwriting, reading, or what not. When a task is unequally difficult for two individuals, other things being equal, that one will be slower for whom the task is more difficult, and that one also will probably make more mistakes. The spelling situation, then, is not peculiar in this respect.

Variations in speed at various levels of difficulty. It is a matter of common observation that a difficult task requires more time than a similar easy task, that on the average one takes longer to spell a difficult word than an easy word. This conclusion from common experience needs no verification, but it is of interest to know the exact changes in speed of spelling as the words become more difficult. What is the nature of the function of average spelling time on word difficulty?

The eleven lists of words, previously described, ranging from very easy to very difficult were used here. The average time required by all subjects to spell the words of each list was found. The results are presented in Table VI.

It appears from this table that while more and more time is needed as the words become increasingly difficult, the rate of increase in time becomes less and less. In general, a given increase in difficulty when the words are already difficult results in a smaller increase in time than an equal increase in difficulty at the level of easy words.

TABLE VI

AVERAGE TIME PER WORD AT DIFFERENT LEVELS OF DIFFICULTY

Word Group	No. of Words In Groups	Av. Time in Seconds	Percentage Misspelled
1	74	3.26	0.0
2	88	4.18	7.50
3	61	4.47	17.51
4	36	4.77	27.48
5	38	4.64	37.54
6	41	4.99	47.51
7	22	5.37	57.39
8	16	5.71	67.42
9	20	5.58	77.60
10	22	5.72	87.64
11	48	5.86	97.50

SUMMARY OF RESULTS

1. In the spelling of words individuals are very likely to maintain at various levels of difficulty approximately the same relative speed. The individual who is fast is likely to remain fast, and the individual who is slow to remain slow whatever the level of difficulty may be. Since, however, the correlation between speeds at different degrees of difficulty varies inversely with the difference in difficulty, the probability of the same relative speed decreases as the difference in difficulty increases.

2. As for accuracy, individuals similarly tend to keep constant their relative standing in accuracy for the various levels of difficulty. The good speller on easy words will very probably be a good speller on medium and difficult words. The correlation between accuracy at two levels of difficulty is, however, highest for small differences in difficulty.

3. There is a positive correlation of .346 between individual standing in speed and individual standing in accuracy for all words. The fast speller, on the basis of the general average, will probably rank fairly high in accuracy of spelling.

4. If the relation of speed and accuracy is considered at the level of easy words, the correlation is high, .631, though this is undoubtedly affected by the relatively large number of zero-accuracy scores. The individual who ranks high in speed on easy words will very likely rank high in accuracy

on easy words. The nature of the correlation between speed and accuracy with respect to medium words is the same, but the correlation is much less, .397. At the level of difficult words there appears to be no correlation between speed and accuracy.

5. It is apparent from the statement of the last paragraph that the level of difficulty does very decidedly affect the degree of correlation. The greater the difficulty the lower the correlation.

6. Speed of spelling decreases as the degree of difficulty increases, but at a decreasing rate.

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(Manuscript received March 1, 1929)

RETROACTIVE EFFECT AND DEGREE OF SIMILARITY

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Early investigators of the phenomenon of retroactive inhibition noted that the retroactive effect was obtained only, or at least most readily, when the interpolated activity exhibited some kind or degree of similarity to the original activity. This relation was noted for both ideational and motor learning, and for both human and animal subjects.[1] These observations immediately raised the question as to the relation of the amount of retroactive effect to the degree of similarity.

Skaggs[2] used memorization of chess formations as the original activity and reconstruction as the method of measuring the amount retained. In one experiment he compared the retroactive effect of the following interpolated activities; (1) The memorization of a new chess formation with the same chess board and chess men as were used in the original activity, (2) The memorization of a new formation with a paper board and five articles as chess men, (3) The solution of problems of multiplication and addition, and (4) The memorization of postcard pictures. He found that the retroactive effect increased with the degree of similarity. It is obvious that the four pairs of activities differ in kind as well as in degree of similarity. In a second experiment Skaggs employed as his interpolated activity three chess formations which apparently exhibited varying degrees of similarity to the original. In this case the retroactive effect decreased with the degree of similarity.

Robinson[3] specified both the nature and the degree of similarity involved. His original material consisted of a short list of consonants presented once. The interpolated activity consisted of a single presentation of a second list of the same number of consonants, and the subjects were then tested for their ability to recall the first list. The original and the interpolated lists sometimes had no letters in common, sometimes one, sometimes two, and the number of common letters was increased until the two lists were identical. The two lists thus exhibited all degrees of similarity of composition from zero to 100 percent. Robinson found that, as a general rule, the

[1] See L. P. Whitely, this JOURNAL, 1927, 10, 489–508, and references there cited.

[2] E. B. Skaggs, Further studies in retroactive inhibition, *Psychol. Monog.*, 1925, 34, (no. 161), 25–32.

[3] E. S. Robinson, The similarity factor in retroactive inhibition, *Amer. J. Psychol.*, 1927, 39, 297–312.

retroactive effect decreased with the increase of similarity, though some exceptions were noted.

Thus in one of the foregoing experiments the retroactive effect increased with similarity and in the other two the opposite relation obtained. On the basis of these experiments and of theoretical considerations, both Skaggs and Robinson have suggested that the retroactive effect might be expected at first to increase and then to decrease as the two activities vary from the maximum of difference to complete identity.

Our investigation was planned to study the relation of the retroactive effect to the degree of similarity, and to discover whether this relation differs for the two methods of measuring retention employed, *viz.* anticipatory recall and relearning. Like Robinson we attempted to specify the nature and the degree of the similarity involved, and for this purpose we employed for original and interpolated materials lists of nonsense syllables which exhibited three degrees of similarity with respect to spelling. Two experiments were performed.

Experiment I

Both the original and the interpolated lists were composed of ten nonsense syllables each presented in serial order until learned. All pairs of original and interpolated lists exhibited one of three degrees of similarity in spelling:

1. Zero degree. The letters of each syllable of the interpolated list were all different from those of the corresponding syllable of the original list (Condition I).

2. First degree. The corresponding syllables of the two lists had but one letter in common, and this common letter occupied the same position in the two syllables. In some lists, this common letter occupied the first position; in others, the second or middle position, and in others, the last position (Conditions II, III and IV).

3. Second degree. The corresponding syllables of the two lists had two letters in common, and they occupied the same positions in the two syllables. In some lists, these two common letters occupied the first two positions; in others, the last two, and in still others, the first and the last (Conditions V, VI and VII).

Condition VIII, of no interpolation, was also introduced to provide a zero point as a basis for measuring the retroactive effect of the various interpolated syllables.

The following table summarizes and illustrates the conditions employed.

	Conditions	Examples Original	Interpolated
I	No letter common	CEP	YOF
II	Last letter common	TAV	BUV
III	First letter common	ZUD	ZIM
IV	Second letter common	MIB	LIG
V	Last two letters common	TID	JID
VI	First and last common	ZOM	ZEM
VII	First two common	NOH	NOQ
VIII	No interpolation	JIC	

The lists of nonsense syllables were learned by the *anticipation* method. Two measures of retention were secured; (1) the percentage of saving in number of repetitions necessary to relearn and (2) the percentage of correct anticipations on the first re-presentation of the original list.

Each subject learned the original list on one day and recalled and relearned it at the same hour the next day. In the case of those conditions which required interpolated learning, the interpolated list was always learned on the next day immediately before the recall and the relearning of the original list. Only one condition was given each week.

Each list of syllables was typed on cardboard and presented on a Chicago memory drum at the rate of two seconds per syllable. The first syllable was used as a cue to anticipation, and hence only nine of the ten syllables had to be learned. The subject was required to spell out the anticipated syllable.

Twenty-nine college students served as subjects. All were first given four practice sittings. As a further precaution against practice effect, the subjects were divided into four groups, and the members of each of these groups learned the eight conditions in a different temporal order. Only one condition was given each week. All subjects used the same original list for each of the eight conditions; but the interpolated list for each condition was varied with individuals as much as the imposed conditions of similarity would permit.

Experiment II

The procedure of the second experiment differed from that of the first in the following respects:

1. Only Conditions I, III, IV, VII and VIII were compared.

2. The lists contained twelve syllables instead of ten, and the subjects were required to anticipate the first syllable. The subjects were thus required to learn twelve syllables instead of nine.

3. The experiment was performed at the University of Wisconsin.[4] The materials were exposed on Hull's automatic exposure apparatus at the rate of 1½ sec per syllable. The syllables were printed in bold gummed letters, ¼ inch in height.

4. Twenty-four undergraduates served as subjects and the five conditions studied were distributed over three weeks.

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[4] The writer wishes to thank Professor V. A. C. Henmon and C. L. Hull for their kind permission to use the facilities of the Psychological Laboratory.

Results and Conclusions

The results of both experiments are given in Table I, which presents for each of the various conditions the average

Table I

AVERAGE PERCENTAGES OF RECALL AND OF SAVING

Exper. I

Cond'ns	No. of cases	Recall Mean	Recall Sigma	Recall P.E.	Saving Mean	Saving Sigma	Saving P.E.
I	29	16.72	22.00	2.75	26.00	33.20	4.15
II	29	6.82	13.69	1.71	22.25	29.34	4.00
III	29	9.90	14.74	1.84	28.80	37.60	4.70
IV	29	11.40	13.64	1.71	31.90	36.00	4.50
V	29	17.46	22.07	2.78	32.93	26.71	3.40
VI	29	23.21	24.40	3.05	29.80	42.00	5.34
VII	29	17.16	18.84	2.36	39.00	24.00	3.05
VIII	28	34.58	18.75	2.39	40.80	32.70	4.16
			Exper. II				
I	24	7.75	7.00	.96	43.60	19.50	2.69
III	24	5.65	4.95	.68	43.70	21.70	2.99
IV	24	6.70	7.30	.97	42.10	18.40	2.54
VII	24	7.50	6.06	.83	45.50	16.30	2.25
VIII	24	16.25	14.10	1.94	57.40	15.50	2.13

percentages of recall and of saving with their sigmas and probable errors. The data justify the conclusions which follow.

1. All interpolated conditions exerted some degree of retroactive effect. The amount retained for the interpolated conditions was invariably less than that for the standard condition of no interpolation for both methods of measurement and for both experiments.

Table II gives the differences between the mean of the standard condition of no interpolation and the means of the various interpolated conditions, together with the ratio of those differences to their probable errors. The majority of these differences are large enough to be statistically significant.

2. The degree of retroactive effect varies with the experiment and the method of measurement.

In the Chicago experiment the size of the differences and their degree of reliability are invariably greater for the method of recall than for the method of saving, while the

TABLE II

COMPARISONS BETWEEN CONDITION VIII AND THE OTHER CONDITIONS

Conditions compared	Recall			Saving		
	Diff. bet. Means	P.E.d	$\frac{D}{P.E.d}$	Diff. bet. Means	P.E.d	$\frac{D}{P.E.d}$
Exper. I						
VIII–I	17.86	3.64	4.90	14.80	5.86	2.52
VIII–II	27.76	2.94	9.44	18.55	5.76	3.22
VIII–III	24.68	3.01	8.20	12.00	6.27	1.91
VIII–IV	23.18	2.93	7.91	8.90	6.12	1.43
VIII–V	17.13	3.65	4.69	7.87	5.37	1.46
VIII–VI	11.37	3.87	2.94	11.00	6.78	1.63
VIII–VII	17.42	3.35	5.23	1.80	5.15	.34
Exper. II						
VIII–I	8.50	2.16	3.93	13.80	3.40	4.08
VIII–III	10.60	2.10	5.00	13.70	3.60	3.80
VIII–IV	9.55	2.30	4.15	15.30	3.32	4.60
VIII–VII	8.75	2.11	4.14	11.90	3.09	3.82

differences in saving are the greater for the Wisconsin experiment and two of these exhibit the greater reliability. Again, the Chicago experiment gave greater and more reliable differences for the method of recall than did the Wisconsin experiment, while the latter gave the greater and the more reliable differences for the method of saving. (See Table II.)

Evidently these results must be due to some of the differences in the conditions employed in the two experiments, probably to the length of lists and to the exposure time.

3. The relation between the degree of retroactive effect and the degree of similarity varies with method of measurement.

(*a*) When measured by the method of recall, the retroactive effect at first increases and then decreases as the degree of similarity increases from zero to approximate identity.

Table III gives the differences between the means of the first and the zero degree of similarity, and between the first and the second degree of similarity, together with their reliability measures. As may be seen the majority of the differences for Exper. I are statistically significant. The differences for Exper. II, when taken alone, may indicate little reliability; but when viewed in the light of the results of Exper. I they are significant in that they consistently show

TABLE III

COMPARISONS BETWEEN THE SEVEN INTERPOLATED CONDITIONS OF EXPER. I

C-c	Diff.	P.E.d	$\frac{D}{P.E.d}$	C-c	Diff.	P.E.d	$\frac{D}{P.E.d}$
I–II	9.90	3.23	3.57	VI–II	16.39	3.49	4.11
I–III	6.82	3.30	2.06	VI–III	13.31	3.56	3.73
I–IV	5.32	3.23	1.64	VI–IV	11.81	3.49	3.38
V–II	10.64	3.26	3.26	VII–II	10.34	2.91	3.55
V–III	7.56	3.33	2.26	VII–III	7.26	2.99	2.42
V–IV	6.06	3.26	1.85	VII–IV	5.76	2.91	1.98

COMPARISONS BETWEEN THE FOUR INTERPOLATED CONDITIONS OF EXPER. II

I–III	2.10	1.17	1.78	VII–III	1.85	1.07	1.77
I–IV	1.05	1.36	.77	VII–IV	.80	1.27	.63

C-c = Conditions compared
Diff. = Difference between means of recall

the same trend as that of the first experiment. The size of these differences and the degree of reliability are greater for Exper. I than for Exper. II, and the explanation here, as elsewhere, apparently lies in differences among the experimental conditions.

(*b*) When measured by the method of saving, both experiments show that the retroactive effect exhibits a slight tendency to decrease with the increase of similarity. But this tendency is not marked nor consistent enough for a definite conclusion.

Nevertheless, the fact that the saving scores do show a different picture from that of the recall scores is unmistakeable (Table I).

4. The influence of the positional factor was studied in Exper. I; but, owing to the limitation of time, this phase of the study was cut short in Exper. II.

The saving scores of both experiments indicate no certain effect of the positional factor.

The recall scores indicate the following tendencies; (1) an identity of the middle letter or the vowel exerts a less retroactive effect than does that of the first or the last consonant, (2) An identity of the first and last letters exerts a less retroactive effect than does that of the first two or the last two letters, and the latter two cases are about equal in effect.

(Manuscript received March 4, 1929)

EYE-MOVEMENT RECORDS IN THE INVESTIGATION OF STUDY HABITS

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An investigation of the studying ability of a group of twenty-one advanced students at Stanford University is elsewhere reported.[1] The average number of lines read by each student during 30-minute periods of rapid reading and Part iii of the Thorndike Intelligence Examination for High School Graduates, given in various forms at intervals of two weeks, were used to measure the ability of the group. All of the subjects, even though they were advanced students, showed improvement, some considerably more than others. As it appeared desirable to obtain an additional measure of their studious activities, we decided to photograph the ocular movements while subjects were reading material from one form of the Thorndike Examination.[2]

The motor behavior of the eyes during the reading process has been the subject of much investigation during the last forty-five years. The history of this development needs no restatement at this time. It was the purpose of our investigation to compare the results from the eye-movement records with the scores made on the Thorndike Examination and on the average number of lines read per 30-min period of rapid reading. The apparatus has been fully described by Miles and Shen[3] in their paper on the eye-movements in the reading of Chinese. The Dodge method of photographing the corneal reflection was used.

[1] H. M. Bell, Measurement and improvement of ability to study, *J. Educ. Psychol.*, (*in press*).

[2] Photographic materials and other expenses connected with the investigation were met from the Thomas Welton Stanford Fund for Psychological Research.

[3] W. R. Miles & E. Shen, Photographic recording of eye movements in the reading of Chinese in vertical and horizontal axes; method and preliminary results, this JOURNAL, 1925, *8*, 344–362.

We tried to make use of the 21 students who were employed in the first part of the investigation of study habits, but finally had to reduce the number to 16. Two subjects, included in the first part, were myopic and could read none of the printed material without glasses. This made it impossible to photograph their eye-movements in reading. Three others withdrew from Stanford and could not be secured as subjects when we were carrying out this part of the study. This left a group of 16 composed of 9 graduate students, 5 seniors, and 2 juniors, all "majors" in psychology and education.

The Reading Material

All the material read was printed uniformly in lines 67 mm in length, which renders comparison of the results possible. All the subjects read the paragraph "Didactic Poetry" taken from Form T, Test 5, of the Thorndike Intelligence Examination, Part iii. This consisted of 26½ lines, six sentences of 32, 30, 34, 11, 28 and 50 words. A total of 185 words. There were 6 divided words. Thus the material was rather difficult reading. In two cases the first attempt to photograph the eye-movements of particular subjects was unsuccessful. For the second sitting the paragraph from Form T, Test 7 was used. In each case the paragraph of material was fastened to the copyholder at a comfortable reading distance from the subject. Small black dots served as pre- and post-exposure fixation points. One was placed at the extreme left and right ends of the top and bottom lines respectively. When the test began these dots were in view but the text could not be seen. The fixation of these dots before and after reading gave points of reference on the photographic records.

At the end of the reading period the subject was given a set of questions to test his comprehension of the paragraph read. Although he was scored on this comprehension test, no further use was made of it. The main purpose of the questions was to produce an attitude of study by informing the subject that he would have to answer a set of questions based upon the material read.

Results

The location of the pauses was determined by placing the records in a small film projector and adjusting this so that the pre-exposure fixation points on the record coincided with the dots at the ends of the lines in the copy. By moving the film the approximate positions of the various fixations along any line of copy were noted and marked on a duplicate copy of the material. The resulting graphic chart made up from the eye-movement records gives us the following information. The percentage of line-length included between the extreme fixations; the number, order, and duration of the fixations; the variation in the location of the pauses at various points in sentences (at easy and difficult phrases and at unfamiliar words); and, finally, comparisons between the reading habits of the students. This method of charting the fixation pauses in reading need not be illustrated for it is in general use.

Table I

Eye-movements in reading the Thorndike intelligence examination, part III, by university students (Time in 1-50 sec)

Subj.	Pauses per line	A.D.	Words per pause	Line per cent	Pause duration	A.D.	Regressions per line	
							Type I[1]	Type II[2]
1	6.3	1.2	1.1	.80	12.1	4.0	0.2	0.5
2	5.7	1.7	1.3	.87	15.8	4.5	0.2	0.5
3	6.2	0.9	—	—	10.8	2.2	0.3	0.1
4	4.7	0.6	1.3	.87	14.3	3.4	0.1	0.7
8	5.2	0.5	1.5	.75	12.9	1.8	0.1	0.0
9	6.3	1.1	1.5	.86	13.7	3.0	0.2	0.8
10	5.3	0.8	1.4	.81	11.9	3.2	0.2	0.4
11	5.4	0.9	—	—	14.5	4.4	0.2	0.3
12	6.8	1.0	1.0	.94	13.5	2.9	0.3	0.5
13	6.1	0.9	1.1	.84	15.8	5.5	0.5	1.2
15	5.7	0.4	—	—	12.5	2.4	0.3	0.3
16	6.5	0.8	1.0	.96	14.0	3.1	0.1	0.2
17	5.6	0.7	1.3	.78	13.6	3.9	0.1	0.2
18	4.0	0.5	1.7	.70	10.4	2.2	0.6	0.1
19	7.0	1.4	1.0	.86	12.3	4.0	0.5	1.1
20	6.9	1.6	1.2	.88	10.3	2.8	0.2	0.7
Average	5.9	0.9	1.3	.85	13.0	3.3	0.2	0.5

[1] Regressions to correct inaccuracies in the location of the first fixation in a line
[2] Other regressions than those occurring at the extreme left of the line

In Table I the reading of the Thorndike material by the group of 16 subjects is analyzed with respect to number of

pauses, words per pause, percent of line between first and last pause, duration of pauses, and types of regressives. The group shows an average of 5.9 pauses per line of 67 mm, with a range of 4.0 to 7.0. The mean A.D. was 0.9. For individual subjects it ranged from 0.4 to 1.7. This is a ratio of 4, whereas for the range of pauses per line it was not quite 2. With respect to pause duration the group shows an average of 13.0 (1 = 1/50 sec) with a range of 10.3 to 15.8.[4] The mean A.D. is 3.3, with a range of 1.8 to 5.5. In regressions to correct inaccuracies in the location of the first fixation in the line the group shows an average of 0.2 per line, *i.e.* such a regression occurred about every fifth line, but subjects 13 and 19 had to make such adjustments in half of the lines they read. Other regressions were made on an average of 0.5 per line. From Table I it seems clear that the number of regressive movements (Type II) bears a relation to the rate of reading. Those who have the most regressives are the slowest or nearly the slowest readers. The fastest readers tend to have few or less than the average number of regressives, but not every slow reader has more than the average, and a good many have less. In other words, slowness may result simply from the number of pauses and the duration of pauses (*e.g.* No. 16) with a minimum of regressives. Swiftness results in the same way from the number of pauses and their duration and demands a minimum of regressives. Regressives most frequently occur at the middle or right-hand end of the line. This is probably to be expected with mature readers.[5]

The perception span or words-per-pause shows an average of 1.3 with a range of 1.0 to 1.7. A number of the words were fixated as many as five times while others were perceived in groups of from 1 to 4 words per fixation. There is a fairly consistent relation between the speed of reading, as indicated by the perception time per line (see Table II) and the number

[4] M. A. Tinker (A photographic study of eye movements in reading formulae, *Genet. Psychol. Monog.*, 1928, *3*, no. 2, 106 and 108) found mean values of 12.7 and 12.8 for scientific prose and for lines not involving formulae.

[5] H. R. Crosland, An investigation of proofreader's illusions, *Univ. of Oregon Publ.*, 1924, *2*, no. 6, 1–168, esp. 135.

of words read per fixation. As would be expected, the rapid readers tend to have the greater spans. But subjects 4, 10, and 20, while they are relatively rapid readers, have fixation spans below the average.

A phenomenon of reading closely related to that of word-span per pause, one that has long been known, is that the first and last fixations for a line do not usually subtend the entire line. These values are given in Table I. The average for the group is 85 percent with a range of 70 to 96 percent. The records with a few exceptions revealed a tendency to cover the material near the left end of the line more thoroughly than on the right; another fact which fits with Crosland's statement that errors in proofreading are more often made at the right. In general, the more rapid readers cover less of the line length naturally in accordance with their greater span per pause.

In theory there should be a high correlation between the words read per fixation and the number of fixations per line. Comparing the columns in Table I we see that such a relationship is present in our group. It is also obvious that when we compare the average number of fixations with the average duration of fixations, there should theoretically be four types of readers: (1) the reader who has a large number of fixations of comparatively long duration; (2) the reader who has a relatively large number of fixations of comparatively short duration; (3) the reader who has a relatively small number of fixations of comparatively long duration; and (4) the reader who has a small number of fixations of short duration. In Table I, No. 16 illustrates the first type; No. 3, the second; No. 4, the third, and No. 18, the fourth type. The first is certain to be a slow reader. The second is more likely to be slow than fast since each added movement requires time to execute it and for the clearing-up period and so tends to increase his total perception time. For the same reason, type three is likely to be a rapid reader and type four is certain to be.

Eye Movements and Studying Ability

The average perception time per line and the average score on the Thorndike tests, used as the measure of studying ability, are compared in Table II. For the perception time,

Table II

THE PHOTOGRAPHED SPEED OF READING COMPARED WITH THORNDIKE TEST SCORE AND WITH RAPID READING SCORE (TIME IN 1-50 SEC)

Subj.	Perception Time per line		Thorndike Score		Rapid Reading (lines)	
	Ave.	Rank	Ave.	Rank	Ave.	Rank
1	76.2	8.5	230	4	734	5
2	90.1	13	186	9	590	10
3	67.0	3	222	5	663	8
4	67.2	5	212	6	726	6
8	67.1	4	187	8	422	14
9	86.3	12	174	11	963	2
10	63.1	2	232	3	665	7
11	78.3	10	175	10	589	11
12	91.8	15	142	14	271	15
13	96.4	16	151	13	1117	1
15	71.2	7	123	15	492	13
16	91.0	14	114	16	565	12
17	76.2	8.5	167	12	818	4
18	41.6	1	236	2	—	—
19	86.1	11	260	1	636	9
20	71.1	6	207	7	932	3
Gen. Ave.	76.3		189		679	

secured by multiplying the average pause duration by the average number of pauses per line,[6] we find an average of 76.3 with a range of 41.6 to 96.4. The most rapid reader took less than one-half the amount of time required by the slowest. A relatively short perception time per line is ranked high (see No. 18) while a long perception time is ranked low (see No. 13). The highest Thorndike score is ranked 1 and the lowest 16. When these series of rankings are compared it is evident that there is a rather high correlation. Rank correlation of all subjects for average perception time per line with the average Thorndike score gives a coefficient of $.64 \pm .10$. If Subj. 19 is eliminated from the ranking, the correlation rises to $.79 \pm .07$. The fact that this student regularly wore glasses but removed them at the time that his

[6] This does not represent the total reading time for about 5 percent must be added for the eye movements themselves.

photographic records were made may account for his large number of pauses per line (7.0) and thus for his relatively long perception time. He was not the most rapid reader but faster than the average (679) and was highest in the Thorndike test. In general, then, we may conclude that there is a high degree of demonstrated relationship between perception time per line and the ability to study as measured by the Thorndike test which itself correlated .74 ± .07 with the college grades of our group. These facts substantiate an earlier conclusion to the effect that the more rapid reader tends to be the more efficient reader.

The comparison between the average perception time per line and the average number of lines read in 30-minute periods of rapid reading practice is also given in Table II. The students did the rapid reading in their own rooms, with no adequate check-up upon the comprehension of what was read. It is obvious that the ranks do not agree well in all cases, especially for Nos. 8, 9, 13, 17 and 19. Rank correlation between these two criteria gave a coefficient of .16±.13. This low correlation between rate of reading on the two types of material—that of the Thorndike Examination and that chosen by the student for rapid reading practice—points to the well-known fact brought out in the work of many other investigators that the rate of reading varies widely with the type of material and with the purpose for which it is read. Comparison of photographically recorded rates of reading, and the average number of lines read in practice-periods brings out certain points of real value in a program of diagnosis of study habits.[7] For instance, Subj. 13 would be considered on the basis of the rapid reading-practice periods the fastest reader in our group; but he was in reality slow. His average perception-time per line in reading the Thorndike material ranks 16; he showed long pause duration, less span than the average and more pauses than the average. The fact that he ranked 13 in average Thorndike score also seems

[7] We do not have eye-movement results taken at the beginning of the improvement program to contrast with these taken at the end, so we can make no correlation of these results with the amount of improvement demonstrated in the six weeks.

to indicate that he was reading at much too rapid a rate during his rapid reading practice. He was in fact simply fooling himself in reference to his own study methods and their results. By using such a comparison of results it is possible to diagnose the study difficulties of students and to make constructive recommendation for remedying them based upon actual knowledge of the particular idiosyncrasies of each student.

Summary

1. Photographic records of the eye-movements of 16 advanced university students were taken when they were reading a paragraph from Form T of the Thorndike Intelligence Examination for High School Graduates, Part iii. Comparisons were made between the average perception-time per line, the average Thorndike test score and the average number of lines read in rapid reading practice-periods.

2. The average number of pauses per line of 67 mm length (7 words) was 5.9 (range 4 to 7), the average duration of pause was .26 sec (range .21 to .32), and the interfixation span covered 1.3 words (range 1.0 to 1.7). Readers vary more in the number than in the duration of pauses.

3. The average perception-time per line of reading material (difficult prose in long sentences) was 1.53 sec.

4. As judged by number of fixations and freedom from regressives, the majority of the readers covered the material at the left end of the lines more thoroughly than they did that at the right.

5. Regressive fixations occurred at the middle or right end of the line more frequently than at the extreme left.

6. The slow readers tend to extend their fixations to the very ends of the lines but the rapid readers do not.

7. Unfamiliar words and the beginnings of sentences have relatively more fixations of a long duration.

8. The most rapid readers as a rule show the most extensive perception spans.

9. There is a comparatively high correlation (about .70) between perception-time per line and scores on the Thorndike test which was found to be a serviceable measure of studying ability.

10. The rate of reading varies widely with the type of material and the purpose of the moment, and the unanalyzed gross rate cannot be taken as representing the student's studying ability.

11. By using three or more measures of studying ability, for example, the Thorndike test scores, the number of lines read in rapid reading practice and the results from eye-movement recording, it is possible to make a practical diagnosis of the studying ability of university students and to formulate constructive suggestions for individual cases.

(Manuscript received March 8, 1929)

A MODIFICATION OF THE DUNLAP CHRONOSCOPE

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In connection with the development of a new *Quadrant Tachistoscope* for studying the reading and legibility of Chinese characters,[1] I required a timing device for measuring the reading reactions in the tachistoscope in somewhat longer units than the usual tachistoscope requires. A simple and inexpensive modification of the Dunlap chronoscope Model II without actually altering any part of the original design met the requirement.[2] The modified form is only a masked transformation of the original which can be instantly restored. As the three present forms are known as Models I, II and III, I shall designate for convenience this modified form Model IV.

In this model as in Model III the large dial on the front of the instrument (Model II) has been bodily elevated and the indicator attached to an added secondary shaft *S'* (Figs. 1, 2) on which is fastened an added intermediate gear wheel *G'*. The teeth (120) and pitch (48) of this added gear wheel are exactly the same as the original revolution-recording gear wheel *G*. The relation of this gear wheel to the spur wheel on the clutch shaft *S* is also the same (10 to 1) as the original gear wheel to its spur wheel on the secondary shaft. Hence the synchronous motor must make 10 revolutions for each revolution of the indicator around the dial and the time value of each of the 100 divisions is 10 times longer than Model II, while Model III increases the time value only 5 times. Another difference is that the original revolution-recording gear wheel *G* is left unchanged.

I have calculated out the unit time values per division on the dial of the four models for various frequencies of the tuning fork for D.C. and for various cycles of A.C. The following table will not only give a clear idea of the differences among the three later models but also will serve as a handy reference for investigators.

UNIT TIME-VALUES OF THE VARIOUS MODELS OF DUNLAP CHRONOSCOPE

For D.C. with tuning fork (arm rev per sec = 1/10 f)				For A.C. (arm rev per sec = 1/5 f)			
Frequency	Rev per sec arm	Rev per sec dial	sigma	Frequency	Rev per sec arm	Rev per sec dial	sigma
Model II (dial rev per sec = arm rev per sec)							
15	1.5	1.5	6.67—	10	2	2	5
25	2.5	2.5	4	20	4	4	2.50
50	5	5	2	50	10	10	1
100	10	10	1	60	12	12	.83+

[1] S. K. Chou, A new quadrant tachistoscope for studying the legibility of Chinese characters, this JOURNAL, 1929, 12, 178–186.

[2] K. Dunlap, The Johns Hopkins chronoscope, this JOURNAL, 1917, 2, 249–252. The construction of the new model was financed from the Thomas Welton Stanford Fund.

Model III (*dial rev per sec = 1/5 arm rev per sec*) *1 dial rev = 5 arm rev*

15	1.5	.3	33+	10	2	.4	25
25	2.5	.5	20	20	4	.8	12.50
50	5	1	10	50	10	2	5
100	10	2	5	60	12	2.4	4.16+

Model IV (*dial rev per sec = 1/10 arm rev per sec*) *1 dial rev = 10 arm rev*

15	1.5	.15	67−	10	2	.2	50
25	2.5	.25	40	20	4	.4	25
50	5	.50	20	50	10	1	10
100	10	1	10	60	12	1.2	8.33+

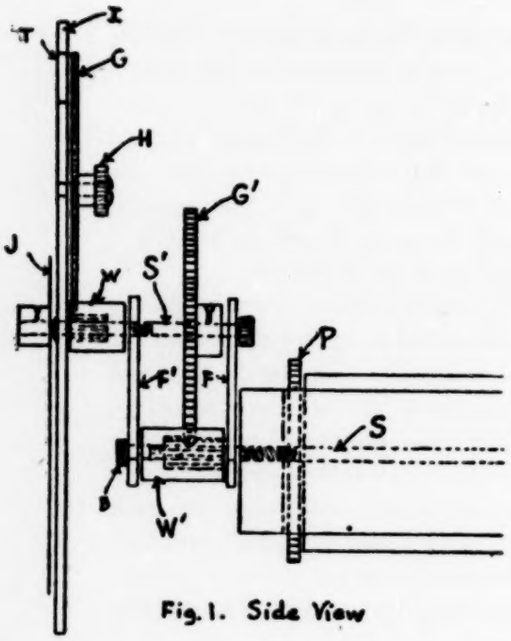

Fig. 1. Side View

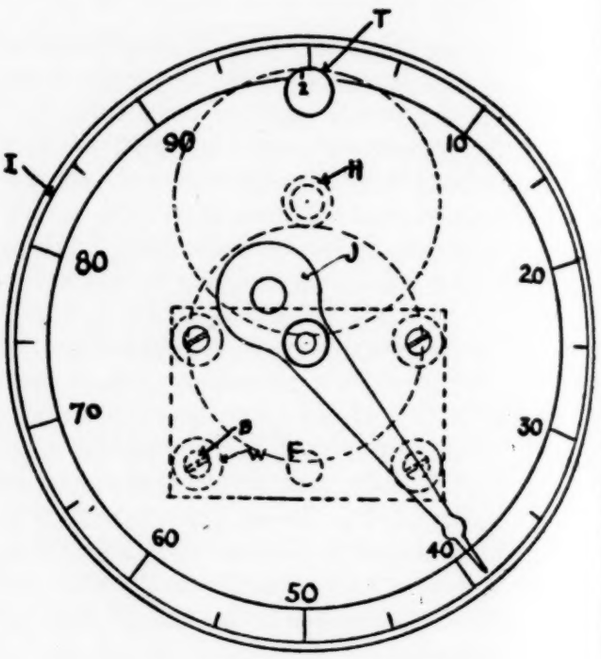

Fig. 2 Front View

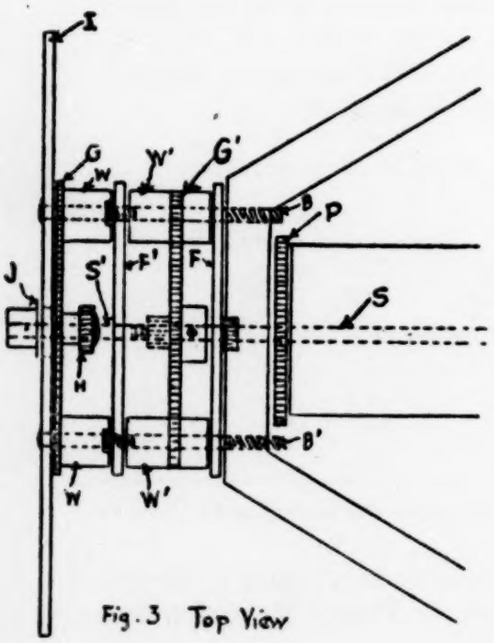

Fig. 3 Top View

MODIFICATION of DUNLAP CHRONOSCOPE

S = main shaft; S' = secondary shaft
P = milled ring
J = hand
I = dial
H = milled head
G = gear wheel; G' = intermediate gear wheel
FF' = copper plates
BB' = bolts
W = wide washers
W' = wide washers added

Reference:
J. Exp. Psy. 1917, 2:249-252

[illegible] SIEGEN K. CHOU (Nanking)

The method for effecting the modification from Model II to Model IV is exceedingly simple and convenient. Two pieces of $\frac{1}{8}$-in. brass plates FF' are milled exactly alike to the size of $2\frac{3}{4}$ in. by $1\frac{7}{8}$ in. Four holes of the same diameter as that of the bolts BB' are drilled on the four corners of the plate F' forming an oblong of $2\frac{1}{4}$ in by $1\frac{3}{8}$ in with the lower two duplicated on the plate F. Midway between the upper two holes another one is drilled on both plates through which the added secondary shaft S' is going to pass, while one is drilled midway between the lower two only on plate F to allow the clutch shaft S to pass. The two plates are separated 1 in apart by two bolts W'' and are screwed to the frame just as the dial I is originally fastened to it. Then the detached dial plate is screwed in turn to the upper two holes on plate F'. The secondary shaft S' that passes through the upper center holes on both plates carries the added intermediate gear wheel G' engaging its spur gear on the clutch shaft S and at the same time carries the original spur gear engaging the original revolution-recording gear wheel G. It is clear that this arrangement does not materially alter any part of Model II and that its original design can be instantly restored by removing all the added parts and refastening the dial plate to the frame.